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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF TYPICAL CONSTANT- AND VARIABLE-AREA EXHAUST NOZZLES AND EFFECTS ON AXIAL-FLOW TURBOJET-ENGINE PERFORMANCE

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EXPERIMENTAL INVESTIGATION OF TYPICAL CONSTANT- AND VARIABLE-AREA EXHAUST NOZZLES AND EFFECTS ON AXIAL-FLOW TURBOJET-ENGINE PERFORMANCE

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SUMMARY

Several turbojet engines with both constant- and variable-area nozzles have been investigated in the NACA Lewis altitude wind tunnel over a wide range of flight conditions with and without afterburning cycles (burning of additional fuel in the tail pipe). The pertinent data from these many studies have been collected and analyzed to extend full-scale nozzle performance to higher exhaust-nozzle pressure ratios and to investigate the effects of constant- and variable-area nozzles on turbojet-engine operation. Velocity coefficients from 0.94 to 0.99 and flow coefficients from 0.95 to 0.99 were obtained for the conical nozzles with exhaust-nozzle pressure ratios up to 3.6. For a variable-area nozzle that was almost planar in both the open and closed positions, a constant velocity coefficient of about 0.98 above the critical pressure ratio was obtained.

Engine performance of several turbojet engines with both constant-area and variable-area nozzles was investigated over a range of thrusts. The time rate of thrust change of a turbojet engine could be materially improved by use of a variable-area as compared with a constant-area exhaust nozzle; at 45,000 feet, a 25-percent thrust change with a variable-area nozzle required only 7 percent of the time required with a constant-area nozzle. The specific fuel consumption obtainable at a given thrust was about the same for both types of exhaust nozzle. For the particular turbojet engine and afterburner investigated with a two-position exhaust nozzle, the nozzle area was too small to permit afterburning to maximum exhaust-gas temperature at an altitude of 5000 feet and too large for the attainment of limiting turbine-outlet temperature at an altitude of 45,000 feet. Specific fuel consumption with afterburning is also penalized at thrusts below the design value for the two-position nozzle because of lowered turbine-outlet temperature and pressure; at 120 percent of rated net thrust (where the two-position nozzle was designed for 135 percent of rated thrust), the specific fuel consumptions were 2.40 and 1.88 for

the two-position and variable-area nozzle, respectively. With a variable-area nozzle, the thrust and specific fuel consumption can be improved because the area can be adjusted to maintain constant turbine-outlet temperature and pressure.

INTRODUCTION

It is a well-known fact that the function of the exhaust nozzle on a turbojet engine is to change the available energy of a hot-gas stream into thrust. Because of this service, the nozzle efficiency influences directly the jet thrust of the engine. Of equal importance is the contribution which a variable-area nozzle can make to the operational performance of the engine.

Most exhaust nozzles in use today have a relatively high efficiency, and improvements in nozzle design therefore do not afford as significant improvement in engine performance as can be realized by a substantial improvement in some of the other less efficient components such as the compressor or the turbine. Probably because the nozzle efficiency is so high, very few quantitative data on nozzles are available although such data are essential to the designer of a jet powerplant and to the evaluation of jet-engine performance. Performance data on full-scale constant- and variable-area exhaust nozzles at nozzle pressure ratios up to 2.0 which were obtained from sea-level static turbojet-engine investigations are reported in references 1 and 2. Investigations of small-scale nozzles with cold air for pressure ratios up to 3.2 are reported in references 3, 4, and 5. The performance data on full-scale constant- and variable-area nozzles were extended herein to exhaust-nozzle pressure ratios of 3.6 by a series of investigations on several turbojet engines under a variety of flight conditions. A comparison of these data with the small-scale nozzle data in the literature is made.

The application of the variable-area nozzle to a turbojet engine increases the flexibility of the engine performance and under certain operating conditions may afford an increase in available thrust and a decrease in specific fuel consumption. Thrust modulation at a fixed engine speed is possible by changing the exhaust-nozzle area, and a much faster rate of change in thrust is possible by changing the exhaust-nozzle area at a fixed engine speed than by changing the engine speed while holding the exhaust-nozzle area constant. Because the same thrust is available over a range of engine speeds if a variable-area nozzle is used, the engine may be operated at the speed and the temperature at which minimum specific fuel consumption is obtained. The area of a constant-area nozzle for a turbojet engine is usually chosen to give limiting turbine-outlet temperature at rated speed for a static sea-level flight condition. Because of Reynolds number effects on the engine at altitude, limiting temperature is often reached at an engine speed less than rated. A change in area from the sea-level value could make rated speed and rated temperature coincident at altitude, if the engine were equipped with a variable-area nozzle. When an afterburner is added to a turbojet engine, a variable-area nozzle is essential if rated engine speed and turbine-outlet temperature and high afterburner efficiency are to be maintained for a range of afterburner fuel flows and flight conditions. Some experimental data taken from turbojet-engine investigations are presented herein by which the quantitative effect of a variable-area nozzle on engine performance variables can be evaluated. This investigation was done at the NACA Lewis laboratory.

APPARATUS

Pertinent data on the axial-flow engines used in this investigation are given in the following table:

Engine	Rated thrust (lb)	Engine pressure ratio	Engine temperature ratio	Compressor pressure ratio	Conical exhaust-nozzle area (sq in.)
A	5200	1.83	3.29	5.2	280
B	3200	1.82	2.95	3.8	171
C	4000	1.84	3.12	4.0	213

These engine data are for rated sea-level static conditions. A typical engine installation in the altitude wind tunnel is shown in figure 1.

The nozzle sizes and types, together with the range of pressure ratios investigated, were as follows:

Number	Nozzle type	Cone half angle (deg)	Outlet diameter (in.)	Outlet area (sq in.)	Instrumentation diameter ratio	Pressure-ratio range investigated	Total nozzle length (in.)
1	Conical, constant area	3.4	19.06	285	0.995	1.2-2.9	17
2	Conical, constant area	3.4	19.06	285	.919	1.2-2.9	17
3	Conical, constant area	2.3	18.88	280	.995	1.1-2.0	20
4	Conical, constant area	4.9	17.15	231	.990	1.2-2.2	20
5	Conical, constant area	8.2	14.76	171	.981	1.2-3.6	20
6	Variable-area, nonplanar clamshell	---	-----	147-270	See text	1.2-3.4	--
7	Variable-area, planar clamshell	---	-----	316-462	See text	1.2-3.3	--

Instrumentation diameter ratio is defined as the ratio of the nozzle-exit diameter to the diameter at the nozzle instrumented measuring station. For nozzles 1, 3, 4, and 5 in the foregoing table, the measuring station was located 1 inch upstream of the exit. (See downstream measuring station, fig. 2(a).) In addition, instrumentation was also located $14\frac{3}{8}$ inches upstream of the exit in nozzle 1; data obtained from this measuring station are designated as nozzle 2 in the foregoing table. (See upstream measuring station, fig. 2(a).)

Survey rakes for the variable-area nozzles were placed 1-inch upstream of the fixed inner lip of these nozzles (fig. 2(b)). The areas at the measuring stations were 298 and 500 square inches for nozzles 6 and 7, respectively. Variable-area nozzle 6 is designated the nonplanar nozzle because the exit shape is elliptical and nonplanar in the closed position, although it is circular in the open position (fig. 3). This nozzle was of the clamshell type with pivot points at the top and bottom of the tail pipe. A motor-driven yoke was used to change the nozzle area. Flexible steel sealing strips were installed on the upstream edge of the movable lips to minimize gas leakage. The exit shape of nozzle 7, designated as the planar variable-area nozzle, was almost circular and in a single plane in both the open and closed positions (fig. 4). The mechanical construction of this nozzle was similar to that of the nonplanar nozzle.

All nozzles were extensively instrumented for measuring total pressure, static pressure, and temperatures. Typical exhaust-nozzle instrumentation rakes installed in a conical nozzle are illustrated in figure 5. The upstream instrumentation rake of nozzle 1 was in a horizontal plane to minimize the effect of its wake on the readings of the downstream rake in the vertical plane.

PROCEDURE

The performance data for the various nozzles were obtained from investigations of axial-flow turbojet engines with and without afterburners. These data were obtained over a range of altitudes from 5000 to 45,000 feet and at simulated flight Mach numbers from 0.2 to 1.1. In order to make a comparison of the specific fuel consumptions with constant- and variable-area nozzles, the three engines were operated over a wide thrust range at several flight conditions with both exhaust nozzles. The time required to vary engine thrust by changing the nozzle area at rated engine speed and by changing the rotating speed with constant nozzle area was experimentally determined. By operating an engine at low and high altitude with both constant- and variable-area nozzles, it was possible to evaluate the effect of changing nozzle area at two altitudes on the maximum obtainable thrust.

The effects of altitude on the performance of a turbojet engine equipped with an afterburner were obtained for both constant- and variable-area nozzle operation. The data for afterburning operation with a two-position exhaust nozzle were obtained from tests with a larger conical nozzle or by locking the planar variable-area nozzle in the wide-open position.

Methods used for the reduction of the data are presented in the appendix.

RESULTS AND DISCUSSION

Constant-Area-Nozzle Performance

Velocity and flow coefficients. - Nozzle performance is presented in terms of effective velocity coefficients and flow coefficients. The effective velocity coefficient is defined as the ratio of actual jet velocity (determined from scale thrust measurements and mass flow) to the effective jet velocity (determined from pressure and temperature measurements in the exhaust nozzle). The flow coefficient is the ratio of the actual mass flow as measured by instrumentation at the engine inlet to the theoretical mass flow determined from measurements in the exhaust nozzle. The coefficients are shown as a function of nozzle pressure ratio, which is defined as the ratio of the total pressure at the nozzle measuring station to the ambient static pressure.

The variation of effective velocity coefficient (hereinafter called velocity coefficient) with nozzle pressure ratio is shown in figure 6 for a nozzle in which both the upstream and downstream instrumentation rakes were installed. Velocity coefficients of about 0.95 and 0.99 were obtained at nozzle pressure ratios of 1.4 and 2.8, respectively, for measurements at both the upstream and downstream instrumented stations (see fig. 6). The loss in total pressure between the two measuring stations was not great enough to affect the velocity coefficients appreciably. The principal pressure losses therefore occur between the downstream instrumented station and the nozzle exit; as a result, coefficients based on a downstream instrumentation station for the subsequent nozzles are considered valid.

Velocity coefficients for nozzles with cone half angles of 2.3°, 4.9°, and 8.2° are shown in figure 7. Although a maximum scatter of about 3 percent occurs in the data at low pressure ratios, a single curve at a value of about 0.97 fits the data for each nozzle. The velocity coefficients presented in figures 6 and 7 were obtained from nozzles investigated on engines A and B, respectively. The differences of the curves in these two figures are attributed to the variation in pressure distributions of the flow entering the nozzles rather than to the nozzle geometries.

Flow coefficients are shown as a function of nozzle pressure ratio at diameter ratios of 0.919 and 0.996 in figure 8 for a nozzle with a cone half angle of 3.4° and an outlet diameter of 19.06 inches. The flow coefficients for a diameter ratio of 0.919 (fig. 8(a)) are about 1 percent lower than the coefficients obtained at a diameter ratio of 0.995. Flow coefficients for nozzles with cone half angles of 2.3°, 4.9°, and 8.2° are shown in figure 9. Coefficients of 0.96 and 0.99 were obtained at pressure ratios of 1.2 and 2.2, respectively, for both the 4.9° and 8.2° nozzles. Data for the 2.3° nozzle scattered too much to determine a definite curve.

Scale effects. - Considerable performance data are available on small-scale nozzles with cold air (references 3, 4, and 5). Investigations with full-scale nozzles on turbojet engines need not necessarily give the same results. A comparison of full-scale data with small-scale data obtained from several different sources is shown in figure 10, where velocity and flow coefficients are plotted as a function of nozzle pressure ratio. Although some differences in cone angles and diameter ratios for the nozzles are presented in this comparison, such differences have been shown to have little effect on the velocity coefficients. (See reference 2.) However, differences in nozzle geometry do affect the flow coefficients; only nozzles with comparable cone angles and diameter ratios are thus presented for the flow-coefficient comparison.

At the low pressure ratios, the velocity coefficients of the full-scale nozzles (which are the curves presented in figs. 6 and 7) are between 0.95 and 0.97 and at the high pressure ratios vary from 0.97 to 0.98. The velocity-coefficient curve for the 7° small-scale nozzle (reference 5) is similar to the full-scale results, but there is considerable disagreement between the curves for references 3 and 4 and the curves of the full-scale nozzles.

The flow coefficients for the full-scale nozzles (data from figs. 8 and 9) increased from 0.96 at low pressure ratios to about 0.99 at high pressure ratios. The curves of reference 3 are from 3 to 5 percent lower at all nozzle pressure ratios. Two factors that may contribute to the differences in the nozzle coefficients are (1) temperature and pressure gradients due to hot exhaust gas from the engines used in the full-scale investigations, and (2) probable differences in boundary-layer thickness.

Variable-Area Nozzles

Velocity coefficients for the two variable-area nozzles investigated are shown as a function of pressure ratio in figure 11. Although a velocity coefficient (fig. 11(a)) of about 0.98 was obtained at a pressure ratio of 1.3 for the nonplanar nozzle in the open position (where the exit shape was planar), coefficients of 0.90 and lower were obtained at high pressure ratios with the nozzle in the closed position (where the exit shape was elliptical and nonplanar). The low velocity coefficients probably result from the fact that the jet issuing from the nozzle in the closed position has a radial component; hence, some of the momentum of the exhaust gases does not contribute to the thrust force produced by the nozzle.

Above the critical pressure ratio (about 1.85), a constant velocity coefficient of 0.98 was obtained for the planar clamshell variable-area exhaust nozzle (fig. 11(b)). At a pressure ratio of 1.2, a velocity coefficient of 0.97 was obtained for the planar nozzle in the open position, and 0.93 in the half-open position where the nozzle was least planar. From these data on variable-area nozzles it is apparent that the degree of planarity of the nozzle exit has an important effect on the velocity coefficient.

Flow coefficients for the variable-area nozzles are presented in figure 12. The nozzle area projected on a plane perpendicular to the engine center line was used in computing the theoretical mass flow; therefore, changes in nozzle area have a large effect on the flow coefficients for the nonplanar nozzle (fig. 12(a)). Flow coefficients in excess of 1.0 attest to the dispersal of some of the flow in a direction other than axial when the nozzle is in the closed position. Flow coefficients for the planar variable-area nozzle, which are not affected by changes in exhaust nozzle area, reach a maximum of about 0.96 at a pressure ratio of 3.2 (fig. 12(b)).

EFFECTS OF EXHAUST NOZZLES ON PERFORMANCE OF TURBOJET ENGINES

Time required for thrust changes. - From a tactical point of view, the time required to change the thrust of a turbojet engine is of great importance. Considerations such as aircraft acceleration or deceleration are directly dependent upon the degree of thrust change obtainable within a given time. Thrust control of a turbojet engine equipped with a constant-area exhaust nozzle is effected by variations in rotating speed. Because of the decreased air density at higher altitudes, less turbine power is available to accelerate the engine while the inertia of the rotating parts remains constant; as a result, the time required to change the thrust increases with altitude for a turbojet engine with a constant-area nozzle. For an engine equipped with a variable-area exhaust nozzle, thrust control can be obtained merely by varying the exhaust-nozzle area. A comparison of the time required to increase the jet thrust from 30 percent and 75 percent to 100 percent of rated jet thrust for engine A operating with each type of exhaust nozzle is shown by the following data at a flight Mach number of 0.21:

Altitude (ft)	Exhaust-nozzle area	Jet thrust (percent rated)		Required engine speed (percent rated)		Time required (sec)
		From	To	From	To	
15,000	Constant	30	100	57.6	100	7.8
	Variable	30	100	64.9	100	5.2
	Constant	75	100	82.2	100	4.2
	Variable	75	100	100	100	1.8
45,000	Constant	30	100	67.2	100	37.4
	Variable	30	100	70.6	100	20.4
	Constant	75	100	81.8	100	24.6
	Variable	75	100	100	100	1.8

(For these thrust variations, the fuel valve was changed at such a rate to keep the exhaust-gas temperature within the prescribed limits.)

A thrust increase from 30 percent to 100 percent of rated thrust can be accomplished with a variable-area nozzle in about 0.67 and 0.55 of the time required with a constant-area nozzle at 15,000 and 45,000 feet, respectively. A thrust increase from 75 percent to 100 percent can be accomplished with a variable-area nozzle in a small fraction of the time required with a constant-area nozzle because no change in engine speed is needed in this thrust range with the variable-area exhaust nozzle.

Specific fuel consumption. - In order to determine the effects of constant- and variable-area exhaust nozzles on specific fuel consumption, data were obtained from three engines that were operated over a wide range of thrust conditions with both nozzles. Thrust with the constant-area nozzle was varied by changing the engine speed; thrust with the variable-area nozzle was varied by changing the nozzle area at constant speed. Specific fuel consumption is plotted as a function of net thrust for each of the engines in figures 13 to 15. The thrust used for this comparison was calculated from pressure measurements upstream of the exhaust nozzle to eliminate the effects of velocity coefficients from the comparison. (From the data on velocity coefficients previously shown, it would be possible to use either a constant- or planar variable-area nozzle with approximately the same velocity coefficients.) Results of operating engine A with constant- and variable-area nozzles at altitudes from 25,000 to 45,000 feet and a flight Mach number of 0.21 are presented in figure 13. The maximum difference between constant-area - variable-speed and variable-area - optimum-speed operation (the speed and nozzle-area combination that will result in the lowest value of specific fuel consumption) is about 5 percent at an altitude of 35,000 feet and 70 percent of rated net thrust.

The operating lines for engine B equipped with a constant-area nozzle indicate lower specific fuel consumptions for some thrust values as compared with the specific fuel consumptions shown for the engine with a variable-area nozzle. (See fig. 14.) Because it is possible to duplicate with the variable-area nozzle any operating point of the constant-area nozzle, equally low specific fuel consumptions are obtainable with both nozzles. Practically identical specific fuel consumptions were obtained for the two modes of engine operation at each thrust investigated for engine C (fig. 15).

In addition to the three experimental engines investigated, the variation of specific fuel consumption with thrust was calculated for a hypothetical axial-flow engine where the component efficiencies were assumed constant. The calculated results indicated that equal specific fuel consumptions were obtained for variable-speed and variable-area - constant-speed operation.

In general, about the same specific fuel consumptions were therefore obtainable for engine operation with either a constant- or variable-area exhaust nozzle for three axial-flow experimental engines and a hypothetical engine with constant component efficiencies. However, if widely different compressor efficiencies were encountered for the two modes of engine operation, the specific fuel consumptions might no longer agree at all thrust levels.

Variation of net thrust with exhaust-nozzle area. - The relation between net thrust and nozzle area for two-axial-flow engines at several altitudes and flight Mach numbers is shown in figures 16 and 17. Rated net thrust for operation with the variable-area nozzles is defined as the thrust obtained at limiting exhaust temperature and rated engine speed for any one flight condition. Changes in altitude between 15,000 and 45,000 feet did not affect the thrust reduction obtained for a given increase in nozzle area. (See figure 16.) Increasing the nozzle area a given amount produced different thrust reduction for the two engines. Part of the difference in the effect of area on thrust results from the different compressor pressure ratios of the engines and differences in component efficiencies. The effect of variations in flight Mach number on the relation between net thrust and exhaust-nozzle area is shown in figure 17. Although a general trend toward increased thrust reduction is noted at the higher flight Mach numbers for a given increase in exhaust-nozzle area, this trend is reversed for engine A at a flight Mach number of 0.92 (fig. 17).

The maximum thrust regulation obtainable with a change in both nozzle area and engine speed is indicated in figure 18 for engine B operating at an altitude of 25,000 feet and a flight Mach number of 1.05. At rated engine speed, increasing the nozzle area from 1 to 1.93 times the rated nozzle area reduced the net thrust from 100 to 24 percent of rated net thrust (fig. 18(a)). Because the thrust curves level off at nozzle areas greater than about 1.8 times rated nozzle area (fig. 18(b)), further thrust reductions can be obtained only by decreasing the engine speed.

Effect of exhaust nozzles on maximum thrust. - The variation of exhaust-gas temperature with engine speed is presented in figure 19 for engines A and B at altitudes of 15,000 and 45,000 feet. These data are for the engines equipped with conical exhaust nozzles that were selected to give limiting exhaust-gas temperature at rated engine speed and an altitude of 15,000 feet. Because of the characteristic decrease in axial-flow-compressor efficiency (reference 6), and the increase in compressor Mach number, the exhaust-gas temperature obtained at a given speed rises with increasing altitude. At an altitude of 45,000 feet, limiting turbine-outlet temperature was obtained at 94 and 91 percent of rated engine speed for engines A and B, respectively.

A variable-area exhaust nozzle provides control of the exhaust-gas temperature at constant engine speed by a change in nozzle area. Increasing the nozzle area to permit operation at rated engine speed for an altitude of 45,000 feet would result in thrust increases of 3 and 6 percent for engines A and B, respectively. The thrust changes obtained for the 6- and 9-percent increases in engine speed are lower than might be expected because of choking at the compressor inlet and the decrease in compressor efficiency.

EFFECTS OF EXHAUST NOZZLES ON PERFORMANCE OF TURBOJET ENGINES WITH AFTERBURNERS

For a turbojet engine equipped with an afterburner (complete description of this cycle can be found in reference 7), the maximum obtainable thrust and specific fuel consumption are influenced by the type of exhaust nozzle. Adding an afterburning cycle to a normal turbojet engine requires a change in the exhaust-nozzle area, which is a function of the increase in exhaust-gas temperature due to the afterburner. In order to operate a turbojet engine equipped for afterburning with or without the afterburner cycle operative, the afterburner must therefore have either a two-position or a continuously variable-area nozzle. Afterburner operation with the two-position nozzle requires the full-open position, whereas the variable-area nozzle is opened to a position that depends upon the degree of afterburning desired.

Effect of exhaust nozzle on maximum thrust. - The variation of turbine-outlet temperature, afterburner combustion efficiency, and exhaust-gas temperature with total fuel-air ratio is shown in figure 20 for a turbojet engine operating with afterburning and a two-position exhaust nozzle in the open position. Although these data are not necessarily general, they do indicate some of the shortcomings of afterburner operation with the constant-area nozzle. Increasing the altitude from 5000 to 35,000 feet raised the total fuel-air ratio at which limiting turbine-outlet temperature was obtained from 0.046 to 0.053 as a direct result of the reduction in afterburner combustion efficiency. A further increase in altitude to 45,000 feet reduced the afterburner combustion efficiency to such a level that it was no longer possible to operate at maximum turbine-outlet temperature. (See fig. 20(b).) At low altitudes, the two-position exhaust nozzle is too small; that is, limiting turbine-outlet temperature is obtained at a relatively low fuel-air ratio. At a high altitude such as 45,000 feet, the nozzle area is too large; that is, limiting turbine-outlet temperature (and thus maximum thrust) is not obtained.

The maximum net thrust obtainable with this afterburner configuration and the possible improvement by the substitution of a variable-area exhaust nozzle is shown in figure 21 as a function of altitude. At altitudes from 5000 to 35,000 feet the thrust increase due to afterburning and with the two-position exhaust nozzle was about 40 percent of rated net thrust. At 45,000 feet, where the maximum turbine-outlet and exhaust-gas temperatures were relatively low as a result of the poor combustion efficiency, the rated net thrust with afterburning could be increased only 18 percent. The thrust increase available at the afterburner exhaust-gas temperatures of 3200° and 3400° R and at a constant turbine-outlet temperature was calculated and is shown in figure 21. In order to maintain the turbine-outlet temperature constant over a range of altitudes, it would be necessary to vary the nozzle area. Afterburning to an exhaust-gas temperature of 3200° R would probably be possible at an altitude of 45,000 feet because a decrease in exhaust-nozzle area would increase both the turbine-outlet temperature and afterburner combustion efficiency. At an altitude of 5000 feet, thrust increases of 43 and 49 percent would be obtained at exhaust-gas temperatures of 3200° and 3400° R, respectively (fig. 21). In order to operate a turbojet engine equipped with afterburning at high exhaust-gas temperatures over a wide range of altitudes, the exhaust-nozzle area must therefore be adjusted.

Effect of exhaust nozzle on specific fuel consumption. - Because of the relatively high cycle efficiency of the normal turbojet engine compared with that of the afterburning cycle, it is desirable to obtain as large a part of the total power output from the turbojet engine as possible. The engine should therefore be operated at maximum turbine-outlet temperature and pressure at all times. For the afterburner with a two-position nozzle, however, any thrust less than the design thrust for the nozzle in the open position will result in lowered turbine-outlet temperatures and pressures and thus excessively high specific fuel consumption. The variation of specific fuel consumption with net thrust is shown in figure 22 for afterburning with a two-position and a variable-area exhaust nozzle. For normal engine operation with both nozzles in the closed position, a specific fuel consumption of 1.28 is obtained at 100 percent of rated net thrust. At full afterburning, limiting turbine-outlet temperature, and 135 percent of rated net thrust, both exhaust nozzles are full open and the specific fuel consumption is 2.31.

Thrust reduction from full afterburning with the two-position nozzle results in lowered turbine-outlet pressure and temperature, whereas with the variable-area nozzle the turbine-outlet pressure and temperature are maintained constant by adjusting the area. For any thrust off the design point for the two-position nozzle with afterburning, specific-fuel-consumption values are higher compared to those obtainable with a variable-area nozzle. At 120 percent of rated net thrust, specific fuel consumptions of 2.40 and 1.88 (a 25-percent reduction) are obtained for afterburning with a two-position and variable-area nozzle, respectively.

The specific fuel consumption of a turbojet engine combination with afterburning can be considerably improved by adjusting the nozzle area to maintain constant turbine-outlet temperature and pressure at thrusts below the maximum value for full afterburning.

SUMMARY OF RESULTS

The performance of several full-scale exhaust nozzles of both the constant- and variable-area types and their effects on the performance characteristics of turbojet engines were investigated over a wide range of simulated flight conditions. Velocity coefficients between 0.94 and 0.99, and flow coefficients between 0.95 and 0.99 were obtained for the constant-area nozzles. These conical-nozzle data did not agree with small-scale data available in the literature. Although velocity coefficients as low as 0.87 were obtained with the nonplanar variable-area nozzle, the performance of the planar variable-area nozzle was comparable to that obtained with the conical exhaust nozzles.

Increasing the thrust of a turbojet engine equipped with a variable-area exhaust nozzle can be accomplished more rapidly by decreasing the nozzle area than by increasing the rotating speed of an engine that has a constant-area nozzle. For instance, at an altitude of 45,000 feet and a flight Mach number of 0.21, increasing the thrust from 75 to 100 percent of rated thrust with a variable-area nozzle requires about 7 percent as long as the time required with a constant-area nozzle.

For three axial-flow turbojet engines investigated at several flight conditions for 50 to 100 percent of rated thrust, about the same specific fuel consumptions were available for constant-area variable-speed as with variable-area and optimum-engine-speed operation.

It was possible to operate a turbojet engine equipped with a variable-area nozzle at limiting exhaust-gas temperature and engine speed, irrespective of the altitude effect on the engine. For two axial-flow engines investigated, adjusting the nozzle area at an altitude of 45,000 feet (to permit engine operation at rated speed), increased the net thrust between 3 and 6 percent.

For the particular turbojet engine and afterburner investigated with a two-position exhaust nozzle, the nozzle area was too small to permit afterburning to maximum exhaust-gas temperature at an altitude of 5000 feet and too large for the attainment of limiting turbine-outlet temperature at an altitude of 45,000 feet.

The specific fuel consumption with afterburning and a two-position nozzle was higher than that obtainable with a variable-area nozzle at all thrusts less than the design value. At 120 percent of rated net thrust (where the two-position nozzle was designed for 135 percent of rated thrust) the specific fuel consumptions were 2.40 and 1.88 for the two-position and variable-area nozzle, respectively.

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APPENDIX - EQUATIONS FOR CALCULATION OF NOZZLE PERFORMANCE

The following symbols are used in this appendix:

A	cross-sectional area, sq ft
B	scale reading, lb
C_f	flow coefficient
$C_{v,e}$	effective velocity coefficient
D	drag, lb
F	net thrust, lb
F_j	jet thrust, lb
g	acceleration due to gravity, 32.2 ft/sec^2
m	mass flow, slugs/sec
P_s	static pressure, lb/sq ft
P_t	total pressure, lb/sq ft
R	gas constant, 53.3 ft-lb/lb-$^{\circ}$F
T_s	static temperature, $^{\circ}$R
T_t	total temperature, $^{\circ}$R
V	velocity, ft/sec
W	weight flow, lb/sec
γ	ratio of specific heats
ρ	density, slugs/cu ft

Subscripts:

a	air
e	effective

f fuel

n exhaust-nozzle exit

r exhaust rake

0 free stream

1 compressor inlet

2 exhaust-nozzle measuring station

For conical nozzles 1, 3, 4, and 5, this station was 1 inch upstream of nozzle exit.

For conical nozzle 2, this station was $14\frac{3}{8}$ inches upstream of nozzle exit.

For both variable-area nozzles, this station was 1 inch upstream of fixed nozzle lip (fig. 2).

Velocity coefficient. - The velocity coefficient is defined as the ratio of velocity attained by a gas issuing from a nozzle to the theoretical velocity with isentropic expansion to ambient pressure (reference 8). For complete isentropic expansion at pressure ratios above the critical value, however, a convergent-divergent nozzle would be required. For converging nozzles where free expansion exists beyond the nozzle exit, the maximum obtainable jet velocity is

$$V_e = \frac{mV_n + A_n(P_{s,n}-P_{s,0})}{m}$$

where V_n was determined from

$$V_n = \sqrt{\frac{2\gamma_2}{\gamma_2-1} gRT_{t,2} \left[1 - \left(\frac{P_{s,n}}{P'_{t,2}}\right)^{\frac{\gamma_2-1}{\gamma_2}}\right]}$$

This velocity is termed the effective velocity with a converging nozzle. (See reference 9.) The effective velocity coefficient is then defined as

$$C_{v,e} = \frac{V_{actual}}{V_e}$$

where

$$V_{actual} = \frac{F_j}{m}$$

and

$$F_j = B + D + m_1V_1 + A_1(P_{s,1} - P_{s,0}) + D_r$$

Flow coefficient. - Nozzle flow coefficient is defined as the ratio of the actual to theoretical mass flow (reference 7).

$$C_f = \frac{m_{actual}}{m_{theoretical}}$$

$$= \frac{W_{a,1} + W_f}{A_nP_{s,n}\sqrt{\frac{2\gamma_2 g}{(\gamma_2-1)RT_{t,2}}\left(\frac{P_{t,2}}{P_{s,n}}\right)^{\frac{\gamma_2-1}{\gamma_2}}\left[\left(\frac{P_{t,2}}{P_{s,n}}\right)^{\frac{\gamma_2-1}{\gamma_2}} - 1\right]}}$$

where

for subsonic flow

$$P_{s,n} = P_{s,0}$$

for supersonic flow

$$P_{s,n} = P_{t,2}\left(\frac{2}{\gamma_2+1}\right)^{\frac{\gamma_2}{\gamma_2-1}}$$

$$W_{a,1} = A_1P_{s,1}\sqrt{\frac{2\gamma_1 g}{(\gamma_1-1)RT_{t,1}}\left(\frac{P_{t,1}}{P_{s,1}}\right)^{\frac{\gamma_1-1}{\gamma_1}}\left[\left(\frac{P_{t,1}}{P_{s,1}}\right)^{\frac{\gamma_1-1}{\gamma_1}} - 1\right]}$$

Thrust. - The jet thrust was calculated from the momentum at the nozzle exit and the excess pressure energy

$$F_j = m\sqrt{\frac{2\gamma_2}{\gamma_2-1}\,gRT_{t,2}\left[1-\left(\frac{P_{s,n}}{P_{t,2}}\right)^{\frac{\gamma_2-1}{\gamma_2}}\right]} + A_n(P_{s,n}-P_{s,0})$$

The net thrust was then obtained by subtracting the inlet momentum of the air entering the engine from the jet thrust

$$F = F_j - m_1V_1$$

Specific fuel consumption. - The ratio of fuel consumption in pounds per hour to net thrust is defined as the specific fuel consumption.

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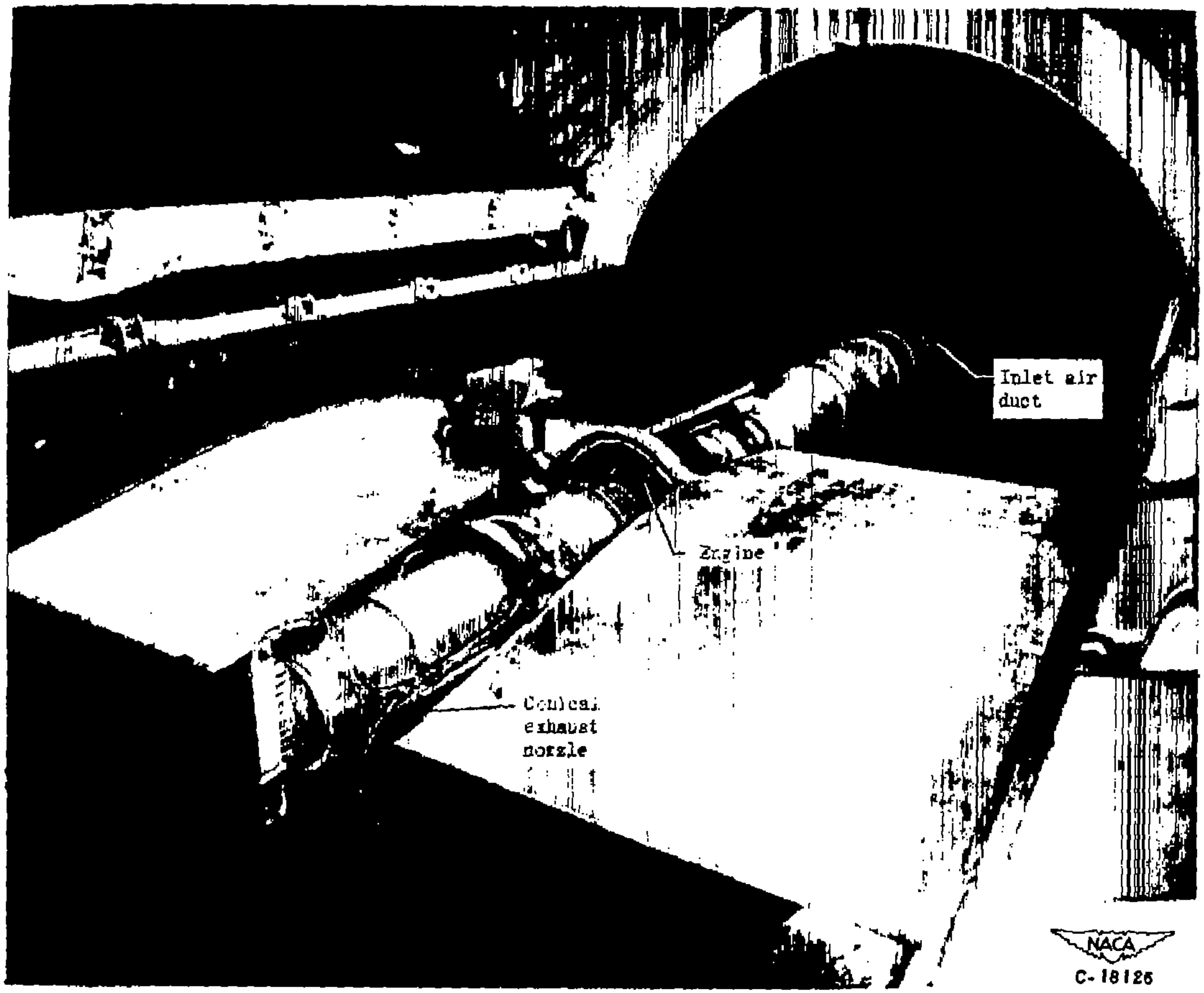
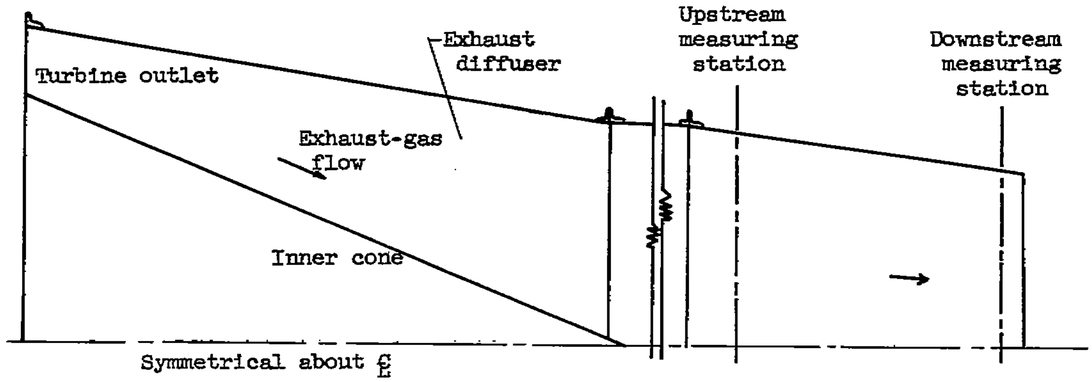
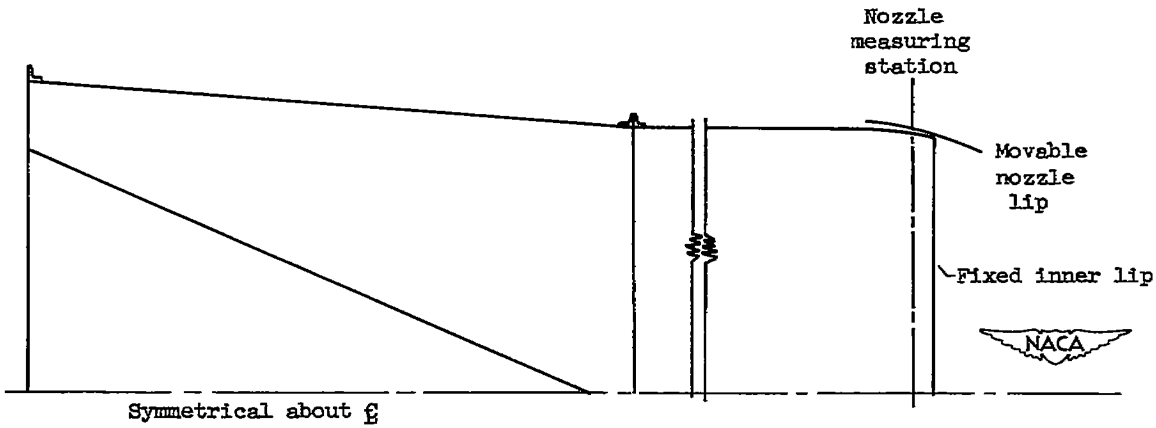


Figure 1. - Installation of turbojet engine in altitude wind tunnel.

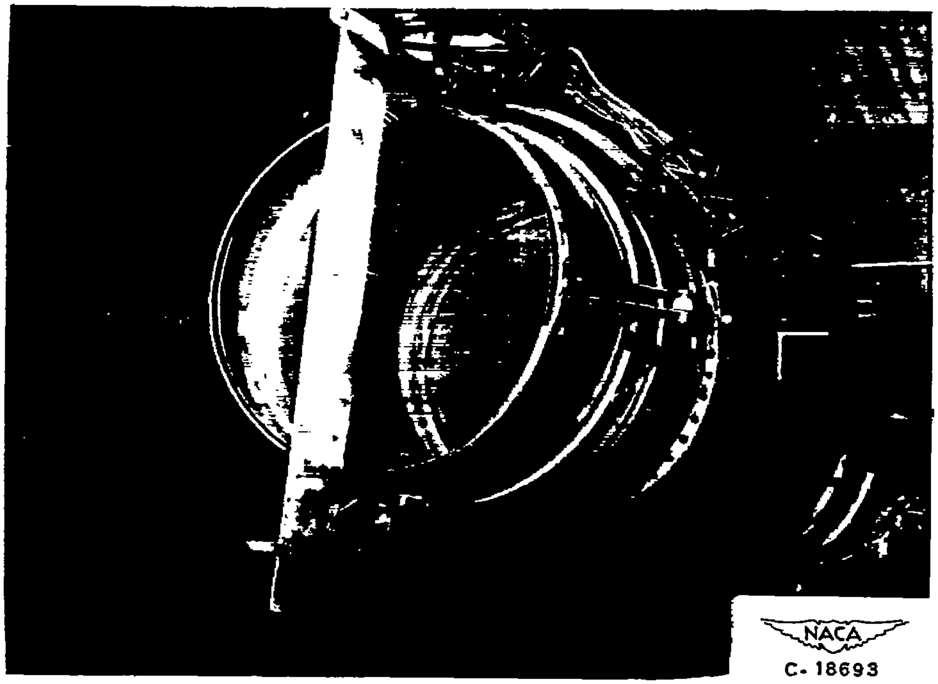


(a) Turbojet-engine exhaust system with conical exhaust nozzle.

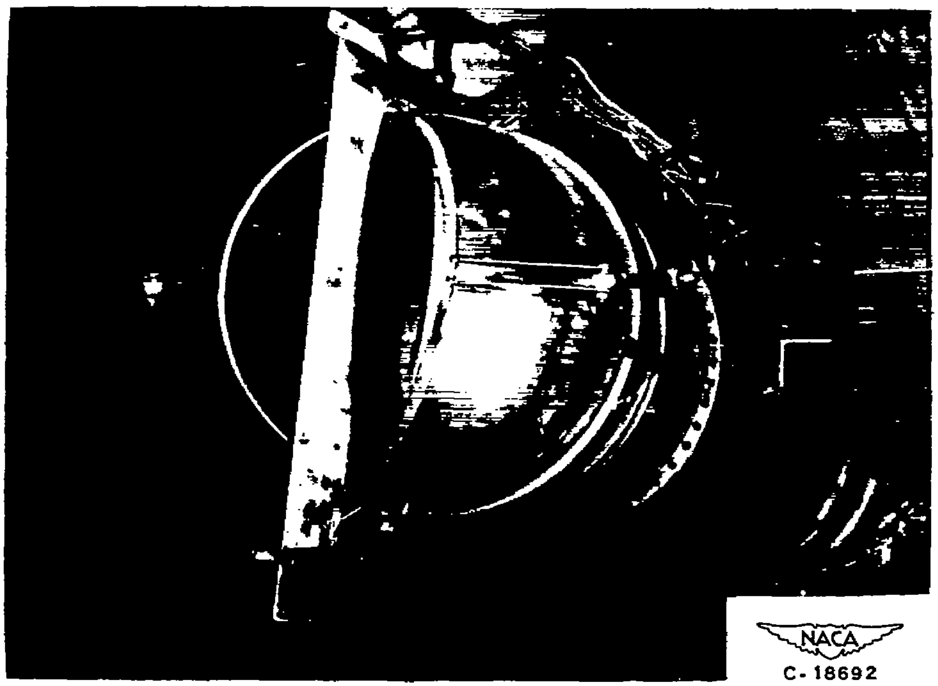


(b) Turbojet-engine exhaust system with variable-area exhaust nozzle.

Figure 2. - Turbojet exhaust systems showing nozzle measuring stations.

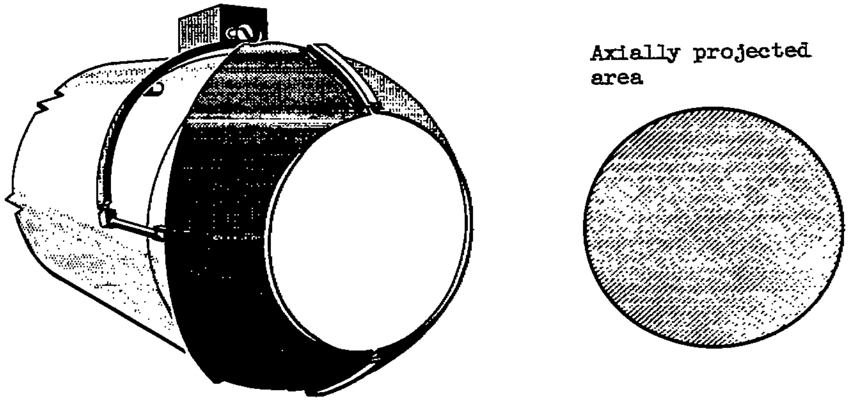


(a) Nozzle in open position.

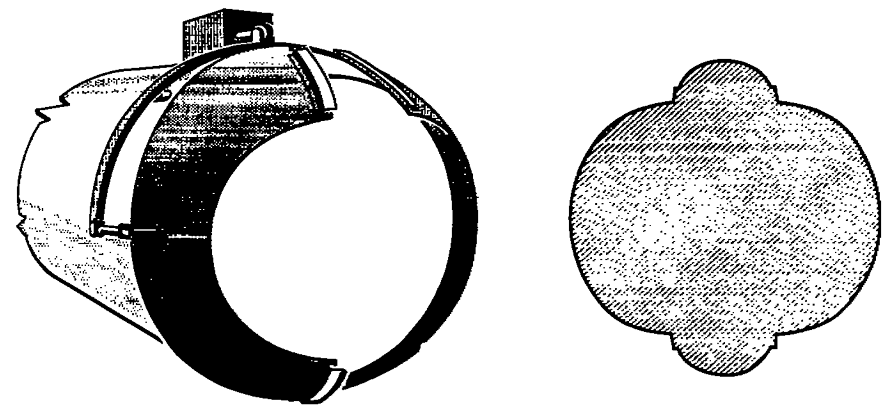


(b) Nozzle in closed position.

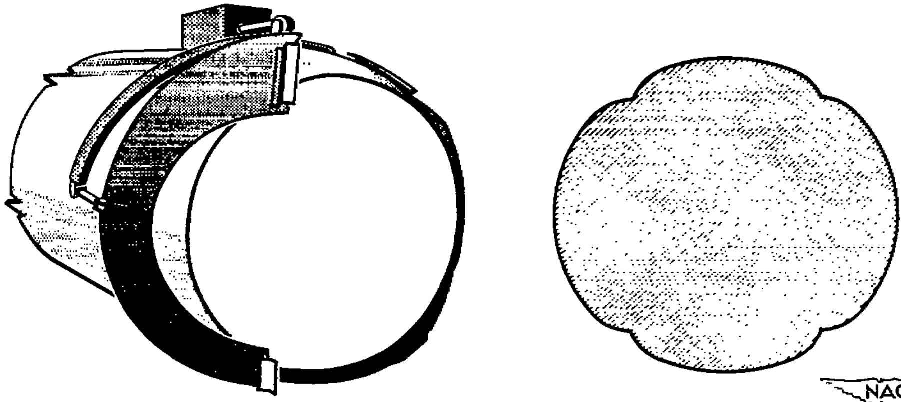
Figure 3. - Tail pipe of turbojet engine with nonplanar variable-area exhaust nozzle.



(a) Full closed.



(b) Half open.



(c) Full open.

Figure 4. - Sketch of planar variable-area exhaust nozzle in several positions.

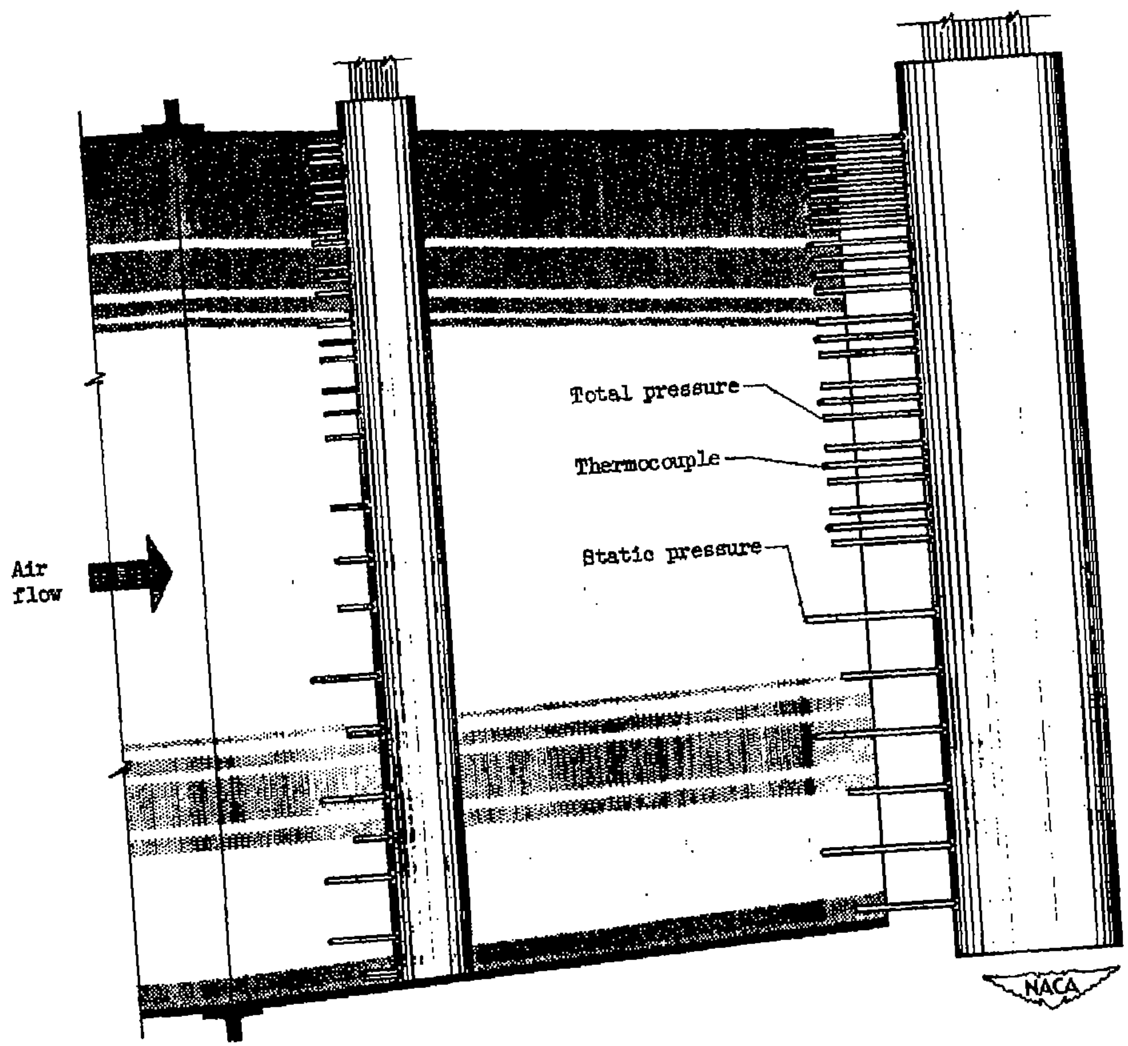
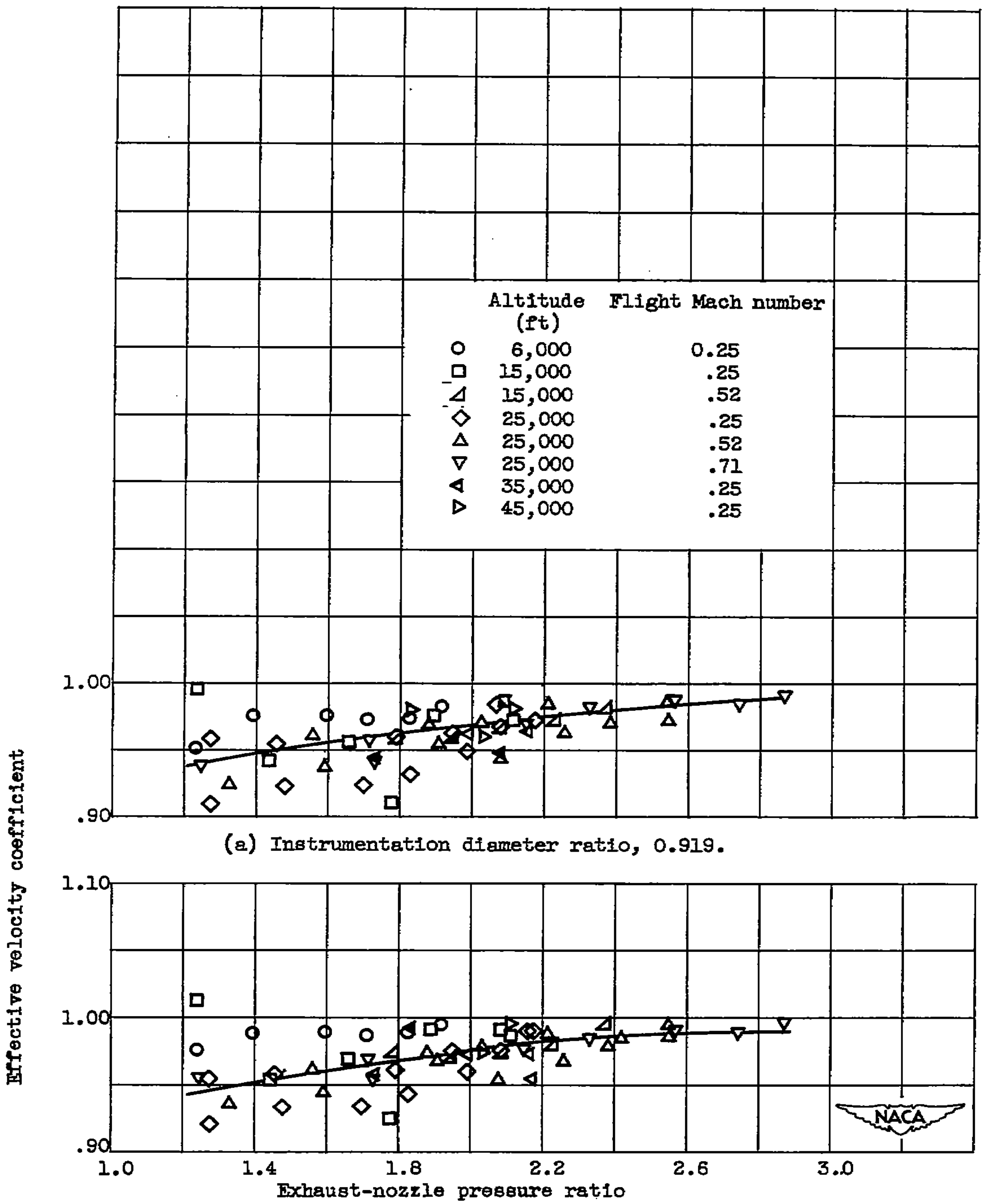


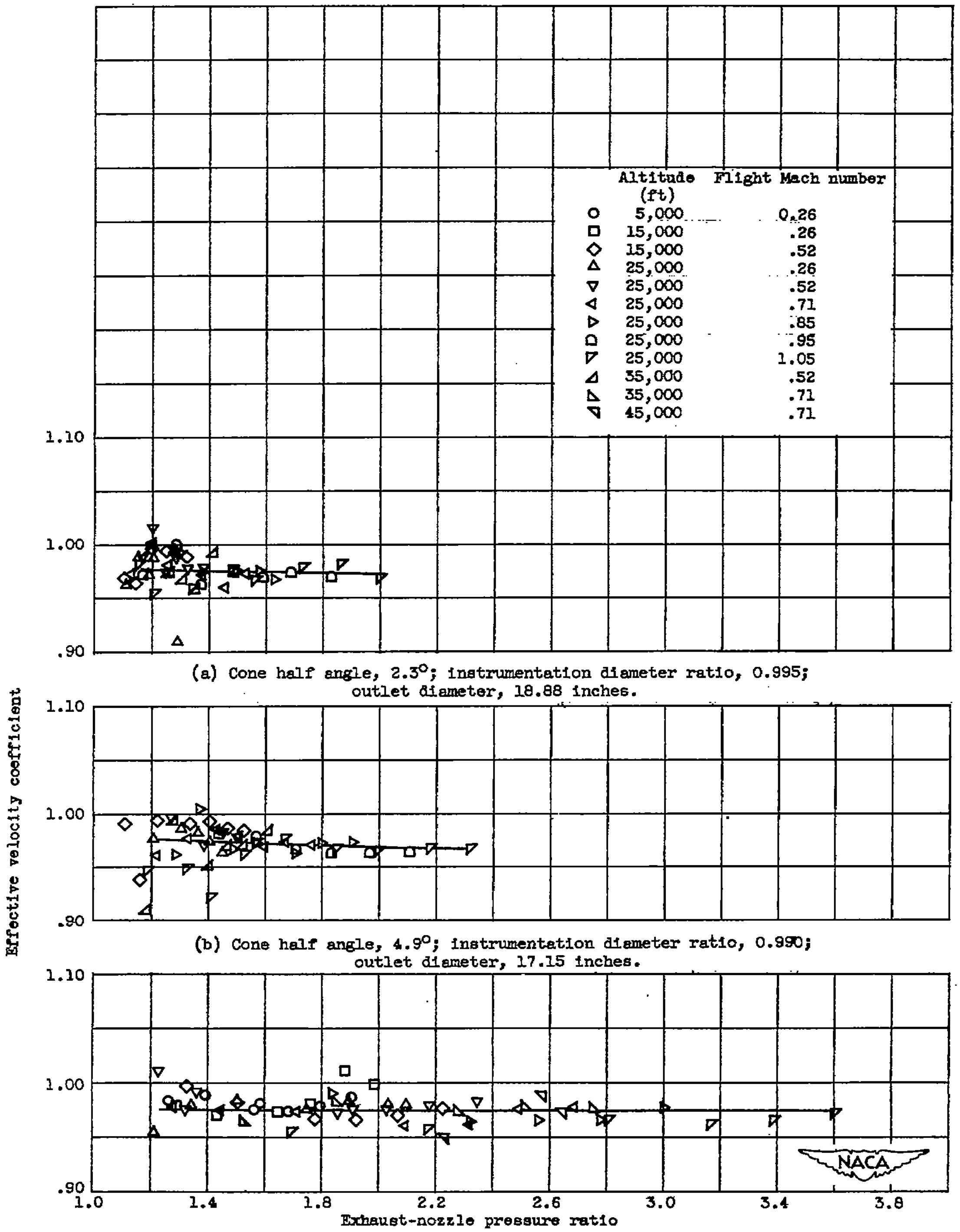
Figure 5. - Typical instrumentation rakes used in exhaust nozzles.



(a) Instrumentation diameter ratio, 0.919.

(b) Instrumentation diameter ratio, 0.995.

Figure 6. - Effect of instrumentation diameter ratio on effective velocity coefficients of conical exhaust nozzles. Cone half angle, 3.4°; outlet diameter, 19.06 inches; nozzle investigated on engine A.

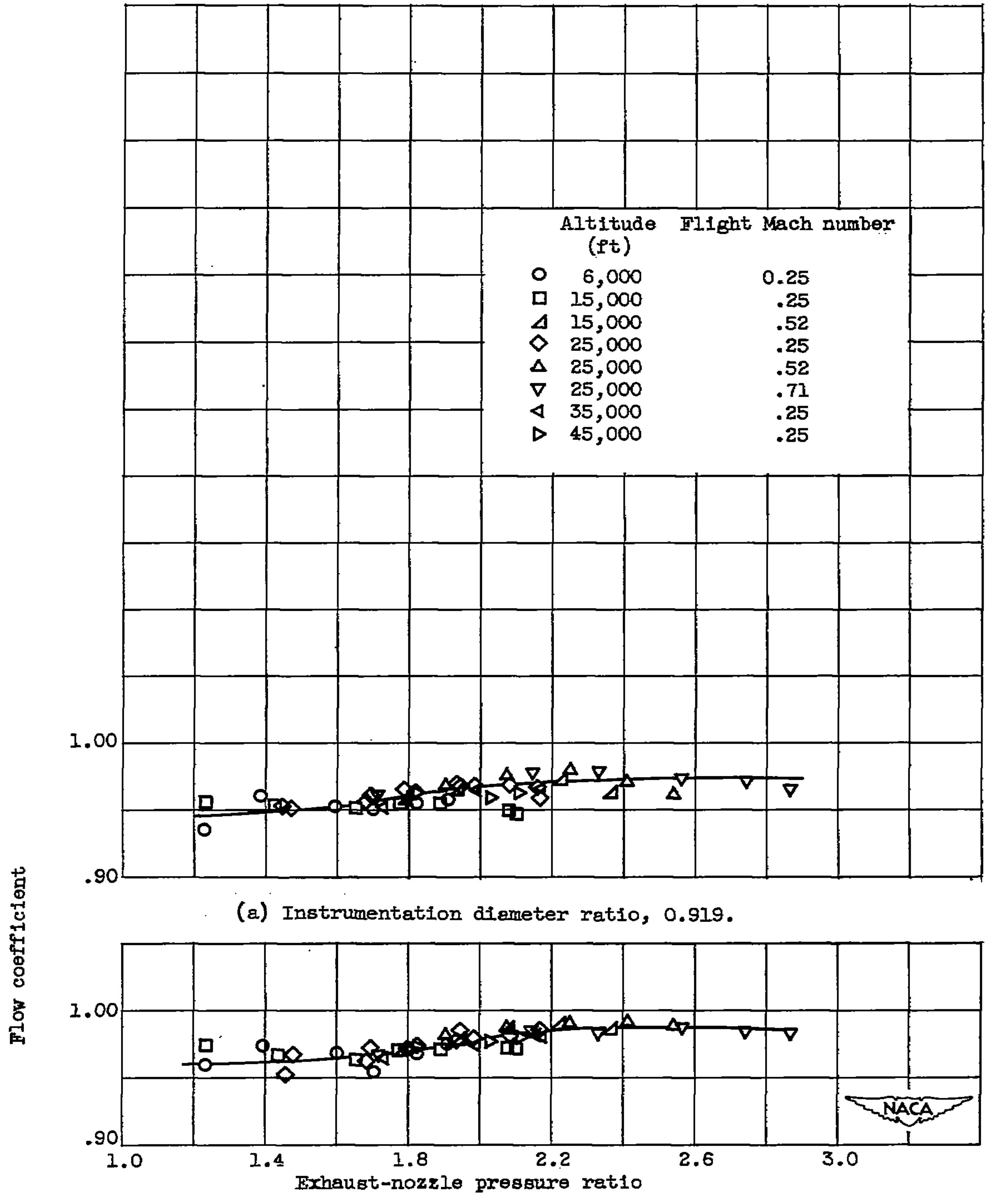


(a) Cone half angle, 2.3°; instrumentation diameter ratio, 0.995; outlet diameter, 18.88 inches.

(b) Cone half angle, 4.9°; instrumentation diameter ratio, 0.990; outlet diameter, 17.15 inches.

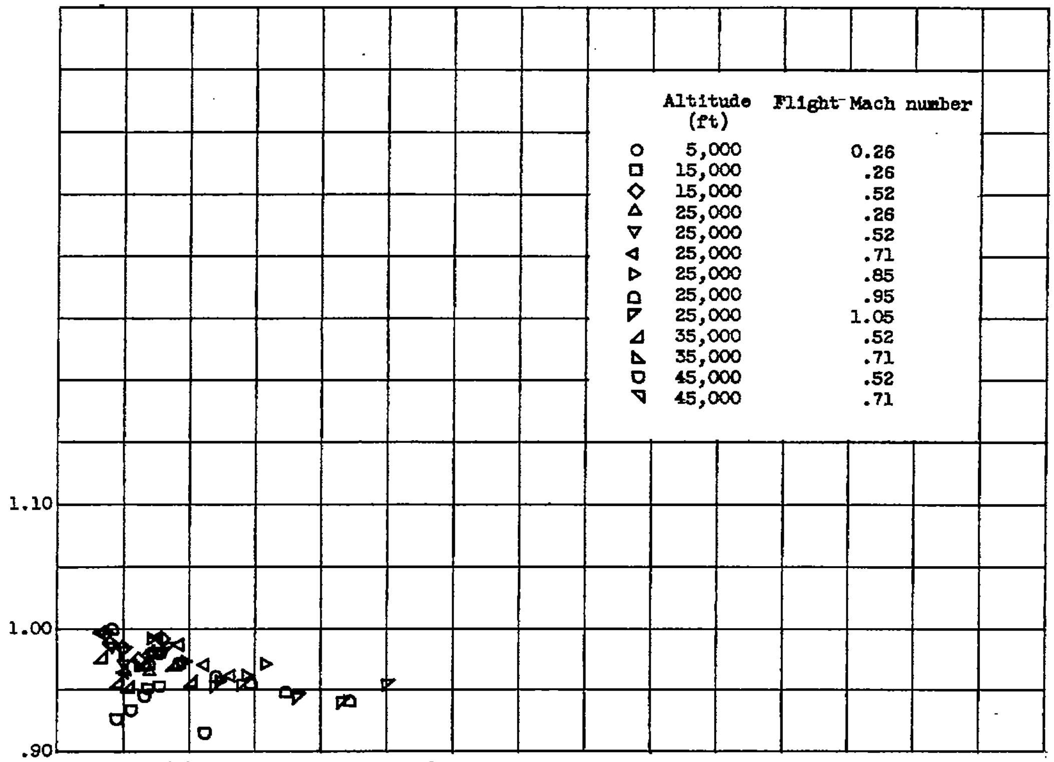
(c) Cone half angle, 8.2°; instrumentation ratio, 0.981; outlet diameter, 14.76 inches.

Figure 7. - Variation of effective velocity coefficient with exhaust-nozzle pressure ratio for conical nozzles with three cone half angles. Nozzles investigated on engine B.

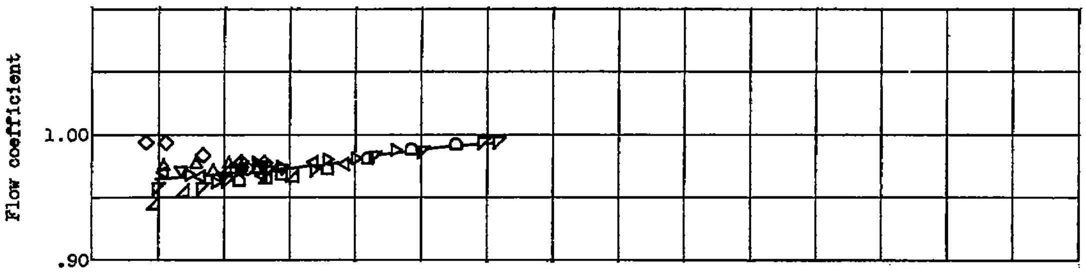


(b) Instrumentation diameter ratio, 0.995.

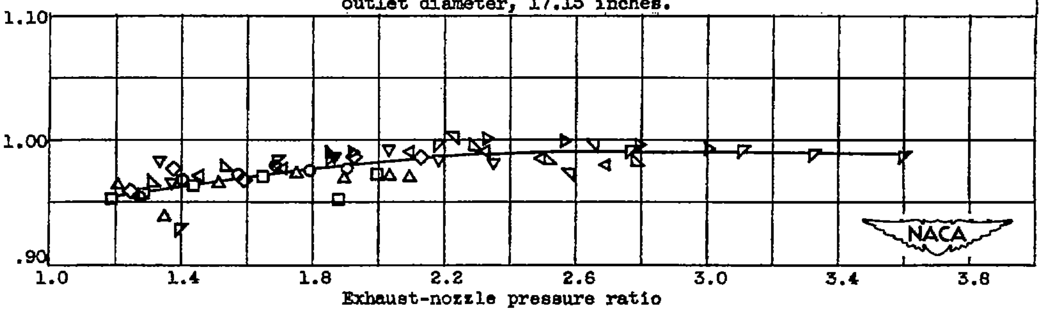
Figure 8. - Effect of instrumentation diameter ratio on flow coefficients of conical exhaust nozzle. Cone half angle, 3.4°; outlet diameter, 19.06 inches; nozzle investigated on engine A.



(a) Cone half angle, 2.3°; instrumentation diameter ratio, 0.995; outlet diameter, 18.88 inches.

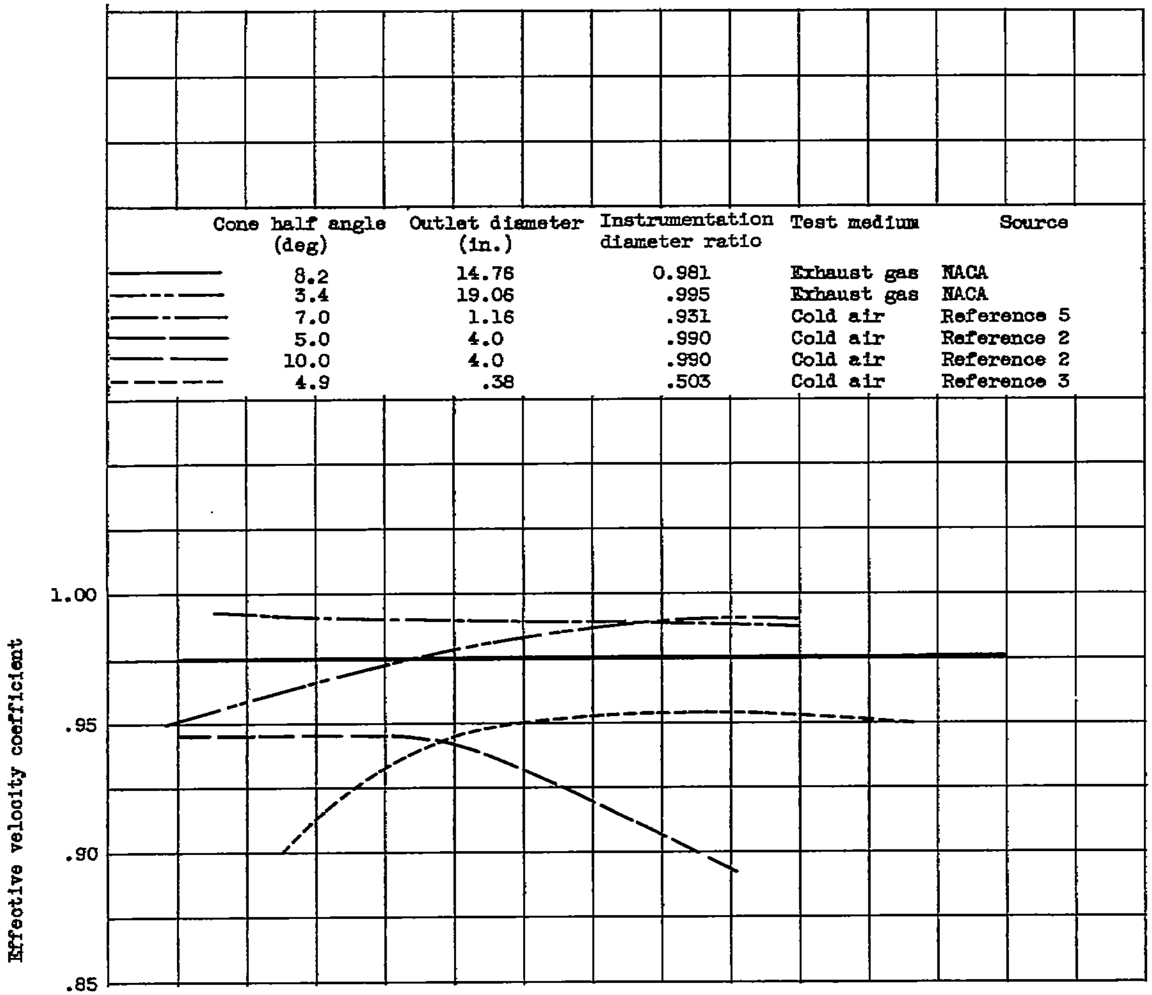


(b) Cone half angle, 4.9°; instrumentation diameter ratio, 0.981; outlet diameter, 17.15 inches.

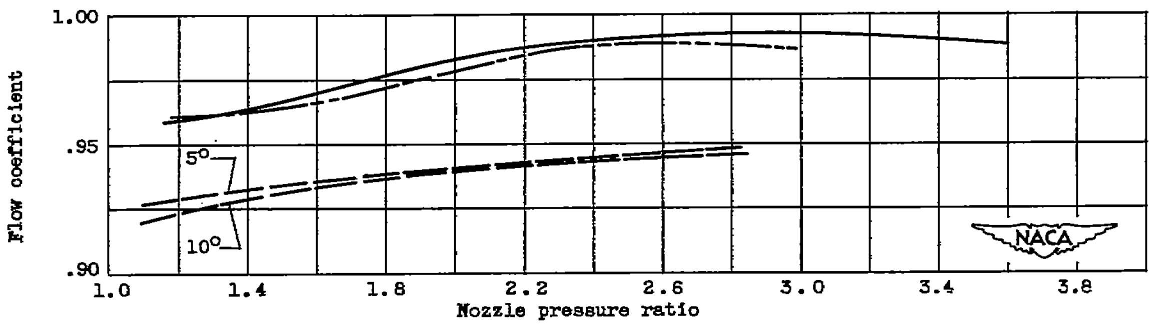


(c) Cone half angle, 8.2°; instrumentation diameter ratio, 0.981; outlet diameter, 14.76 inches.

Figure 9. - Variation of flow coefficient with exhaust-nozzle pressure ratio for conical nozzles with three cone half angles. Nozzles investigated on engine B.

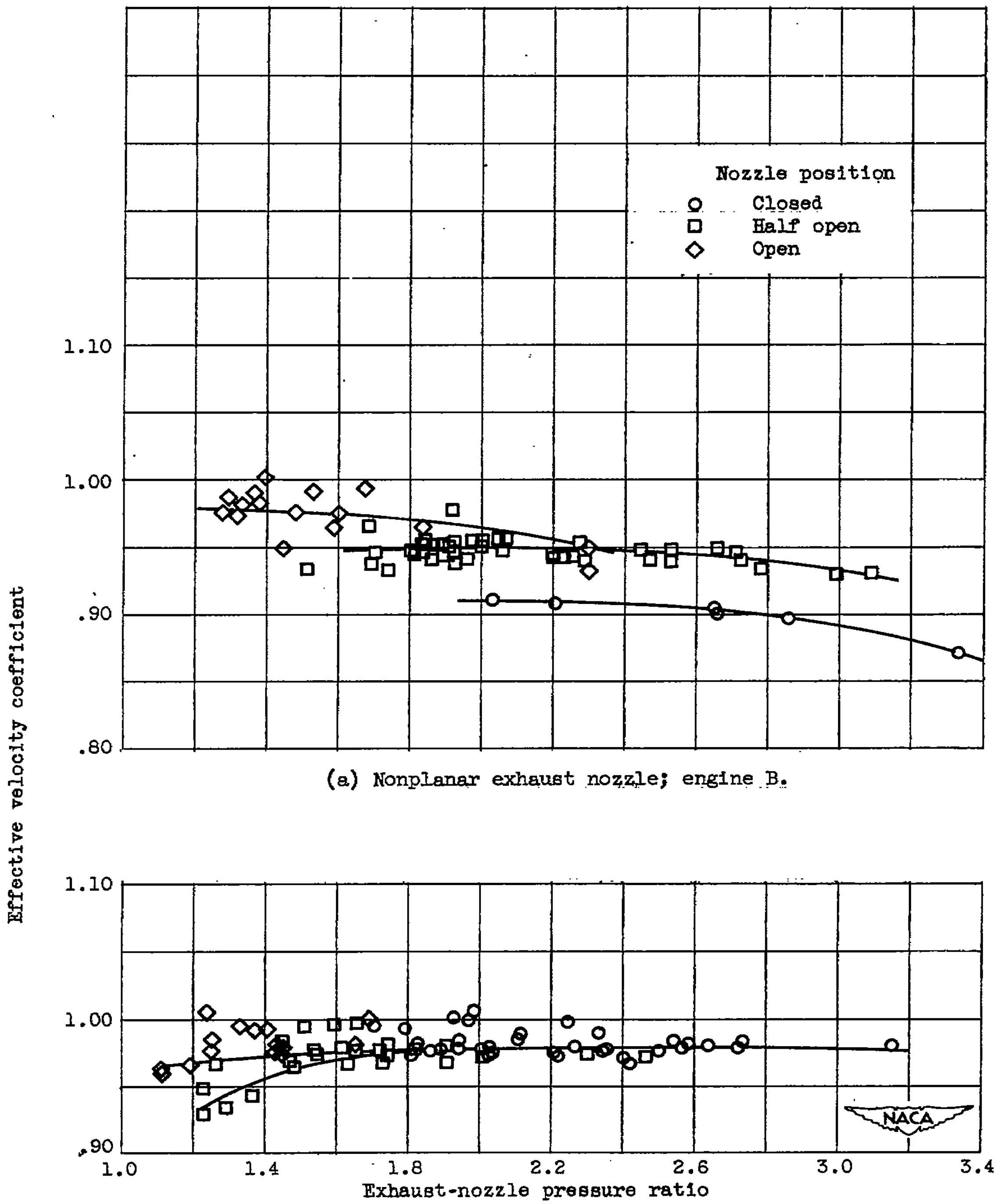


(a) Effective velocity coefficient.



(b) Flow coefficient.

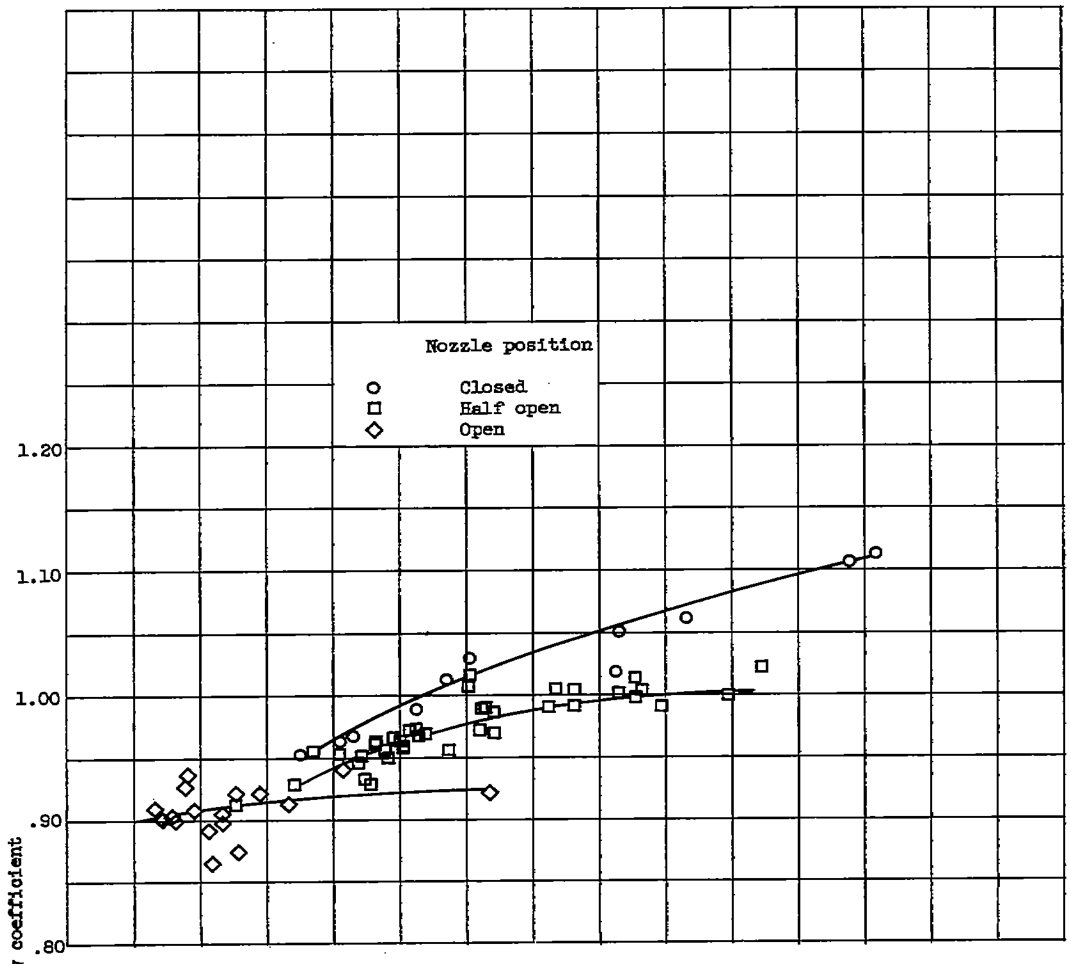
Figure 10. - Comparison of nozzle coefficients obtained from full-scale conical nozzles on turbojet engines and from small-scale nozzles in cold air.



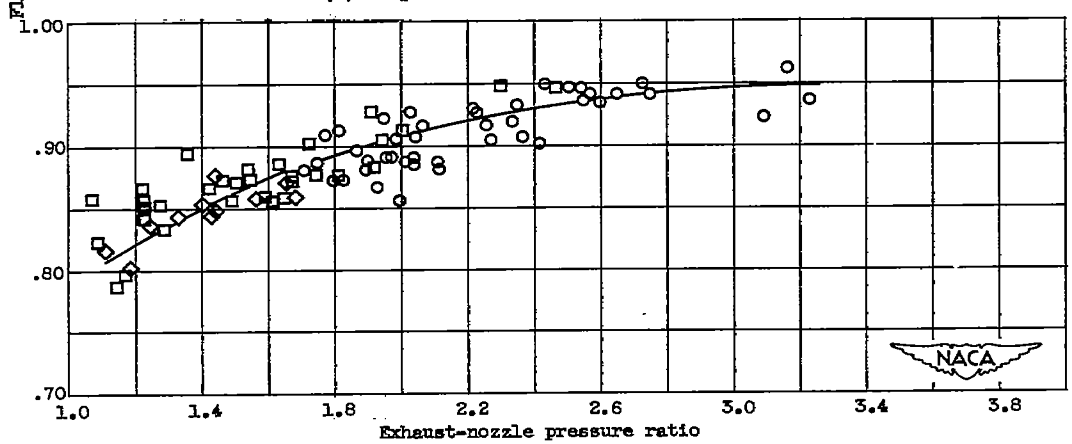
(a) Nonplanar exhaust nozzle; engine B.

(b) Planar exhaust nozzle; engine A.

Figure 11. - Variation of effective velocity coefficient with exhaust-nozzle pressure ratio for clamshell variable-area exhaust nozzles over wide range of flight conditions.

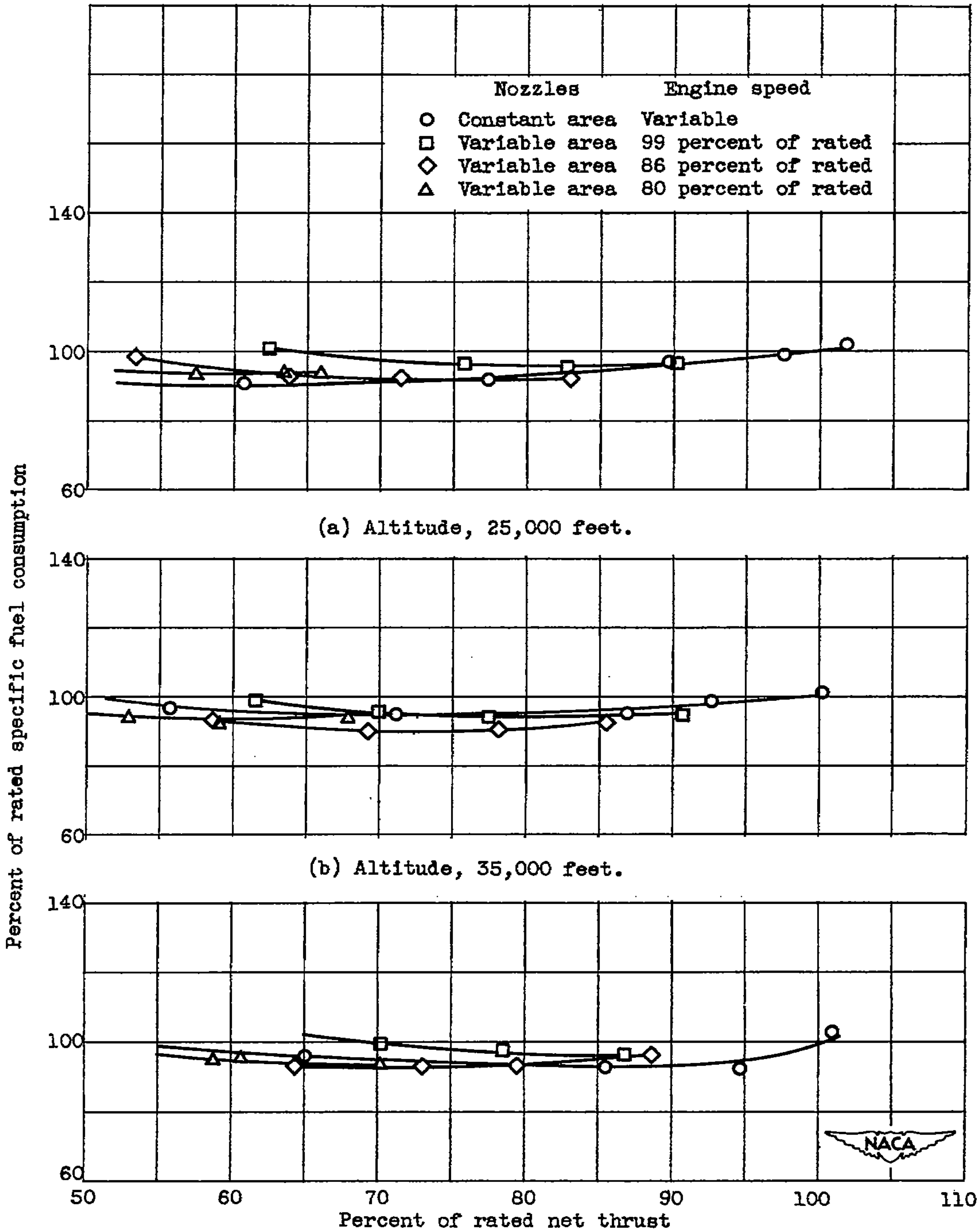


(a) Nonplanar exhaust nozzle; engine B.



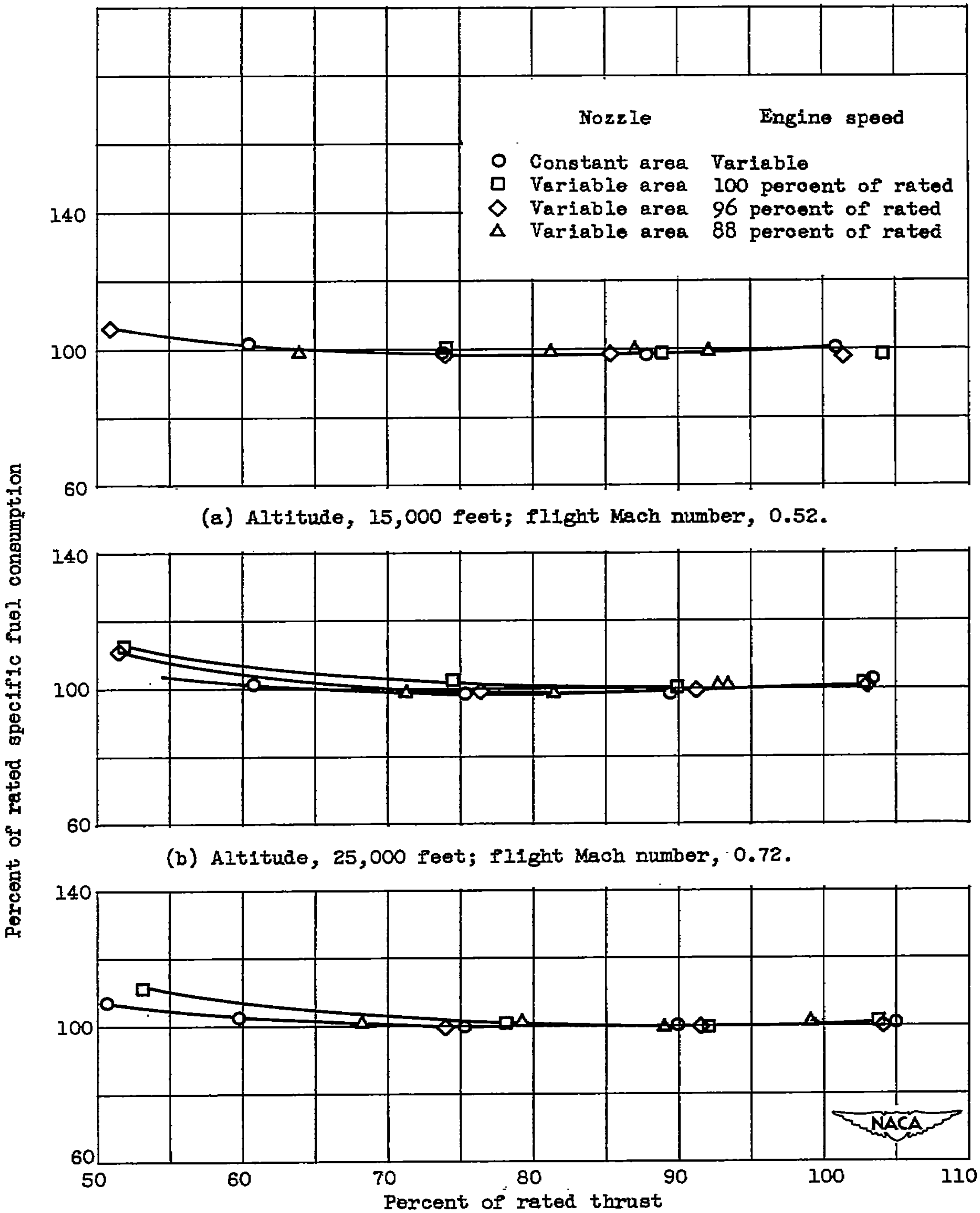
(b) Planar exhaust nozzle; engine A.

Figure 12. - Variation of flow coefficient with exhaust-nozzle pressure ratio for clamshell variable-area nozzles over wide range of flight conditions.



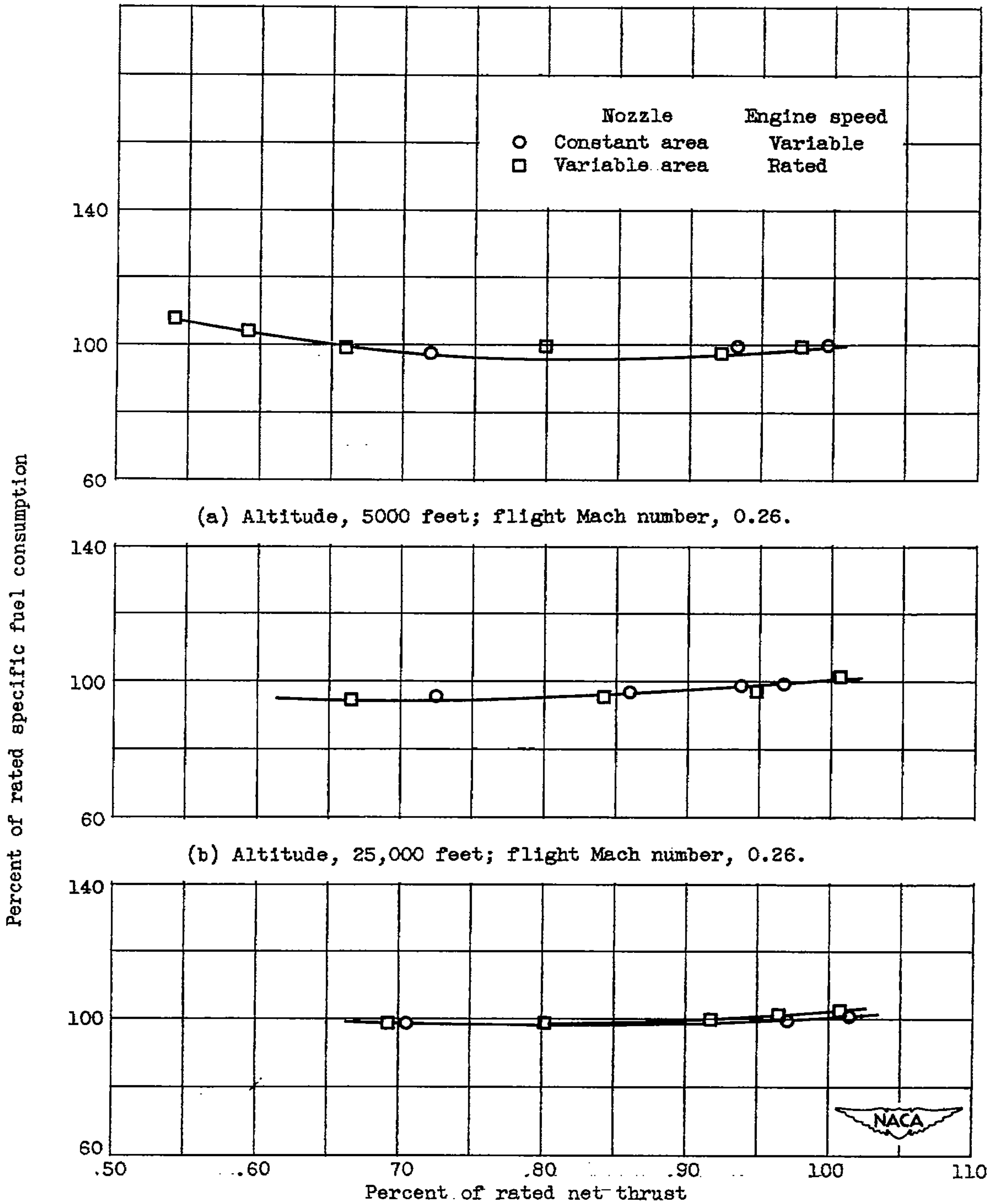
(c) Altitude, 45,000 feet.

Figure 13. - Comparison of specific fuel consumption and net thrust for constant- and variable-area exhaust nozzles for engine A. Flight Mach number, 0.21.



(c) Altitude, 25,000 feet; flight Mach number, 0.85.

Figure 14. - Comparison of specific fuel consumption and rated thrust for constant- and variable-area exhaust nozzles for engine B.

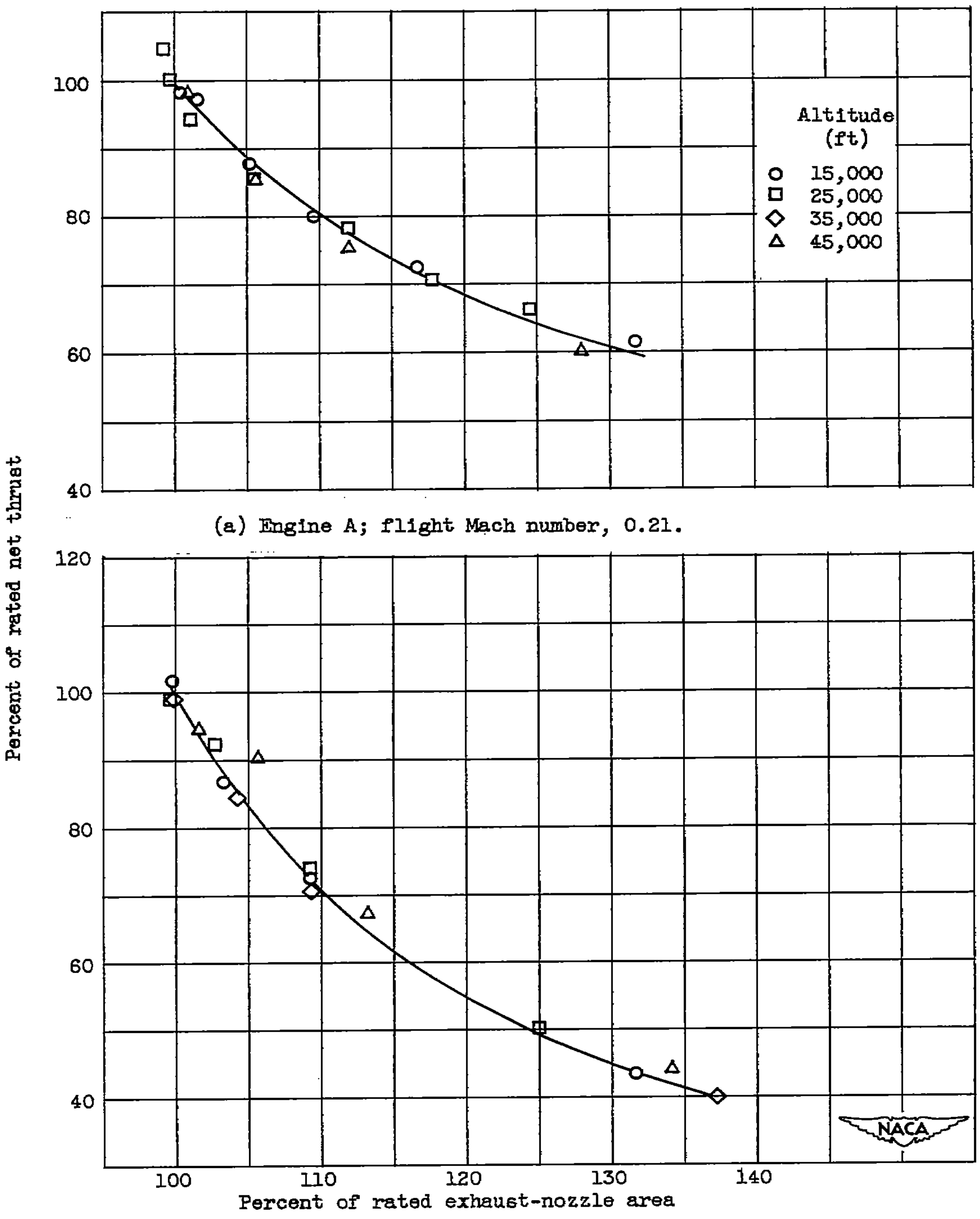


(a) Altitude, 5000 feet; flight Mach number, 0.26.

(b) Altitude, 25,000 feet; flight Mach number, 0.26.

(c) Altitude, 25,000 feet; flight Mach number, 0.91.

Figure 15. - Comparison of specific fuel consumption and net thrust for constant- and variable-area exhaust nozzles for engine C.



(b) Engine B; flight Mach number, 0.52.

Figure 16. - Variation of net thrust with exhaust-nozzle area for two turbojet engines operated over range of altitudes at rated engine speed.

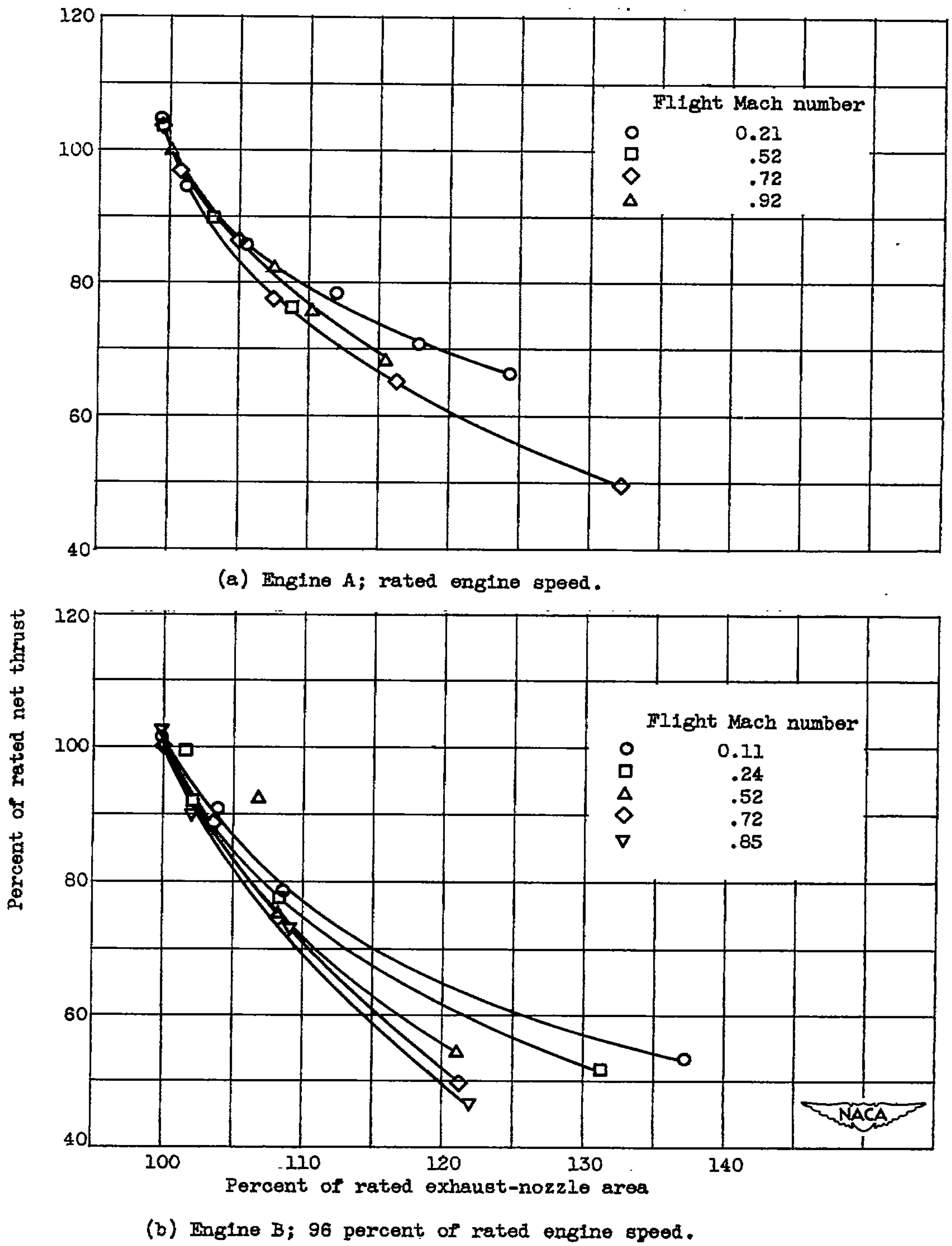


Figure 17. - Variation of net thrust with exhaust-nozzle area for two turbojet engines over range of flight Mach numbers. Altitude, 25,000 feet.

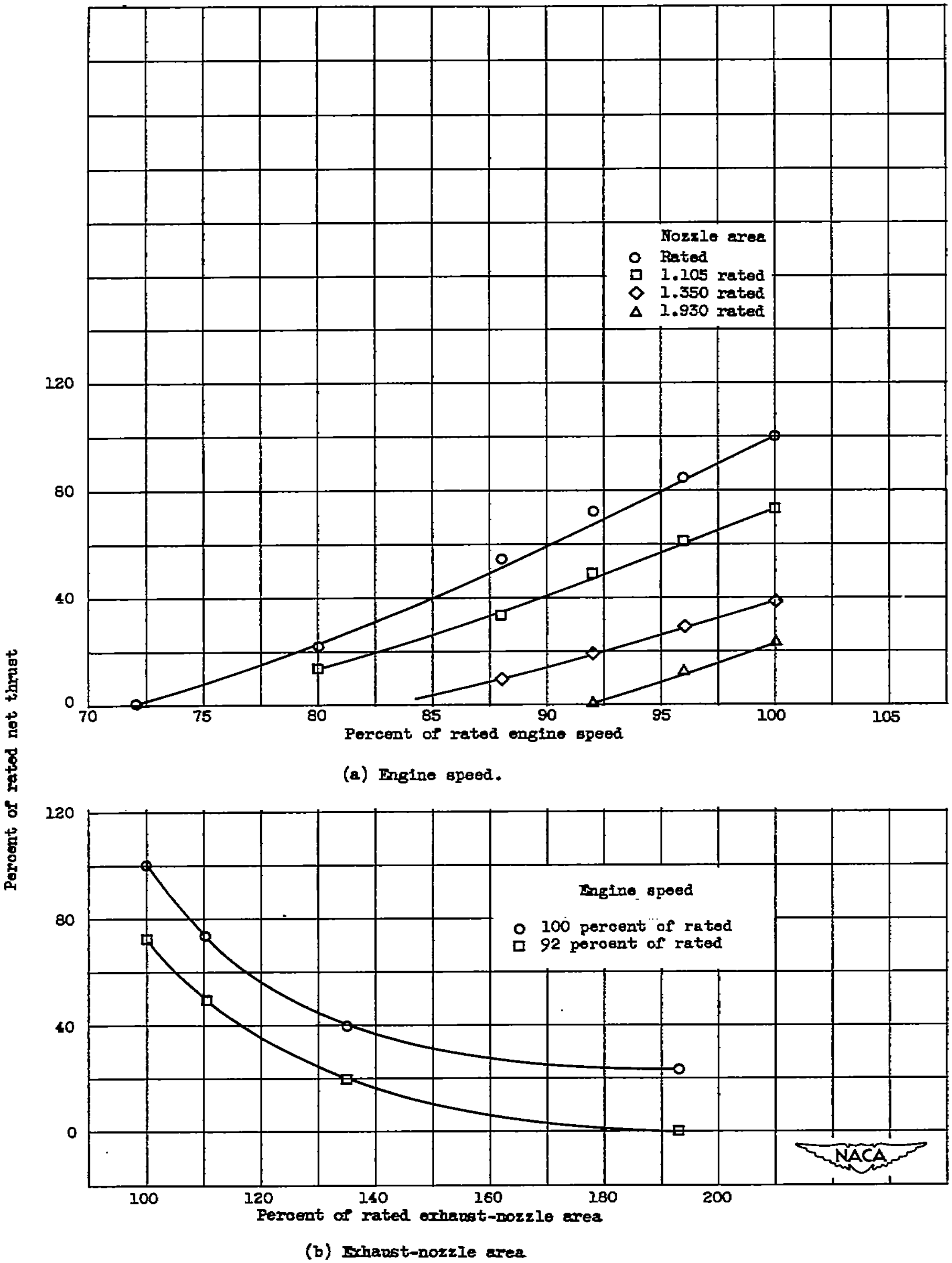
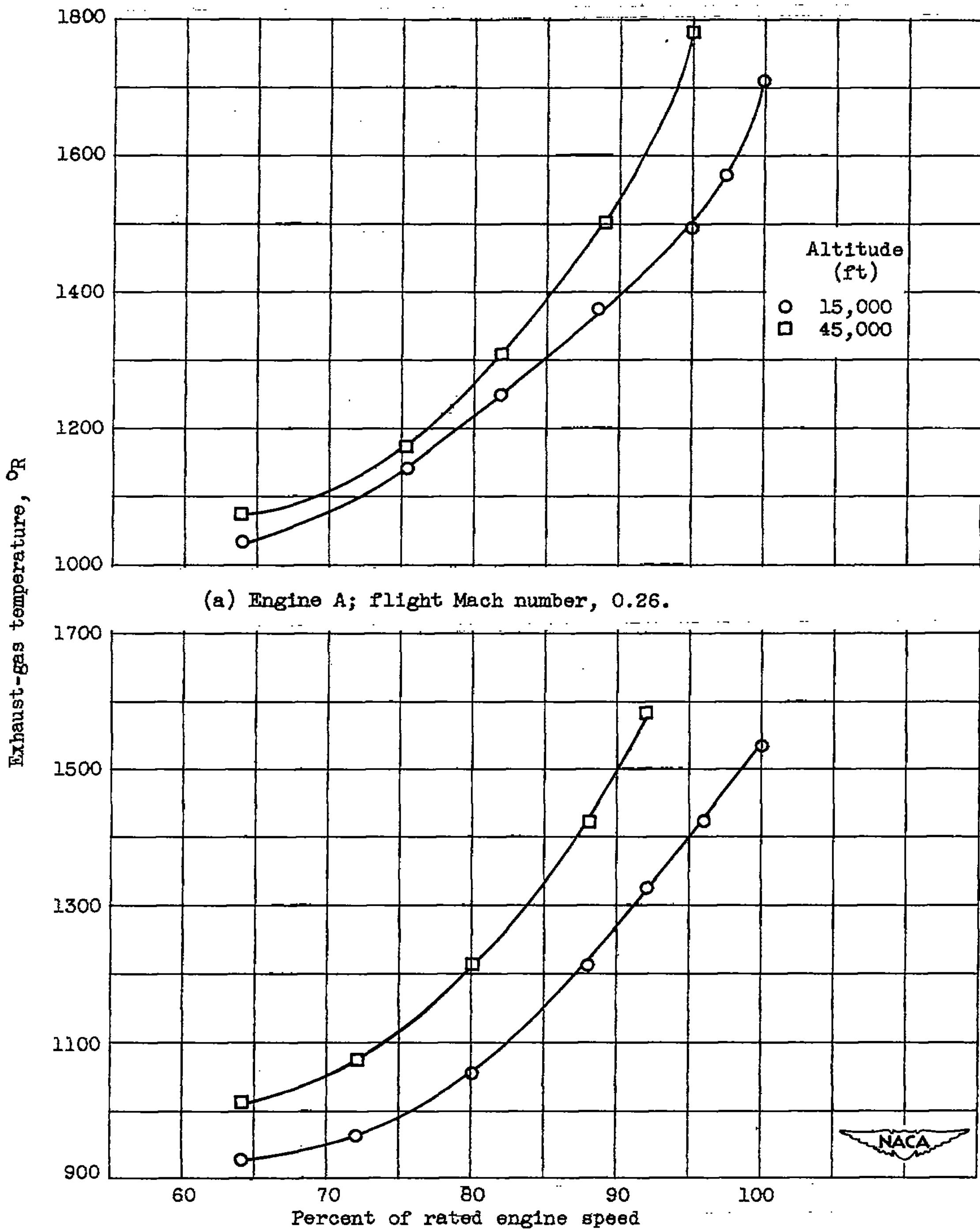


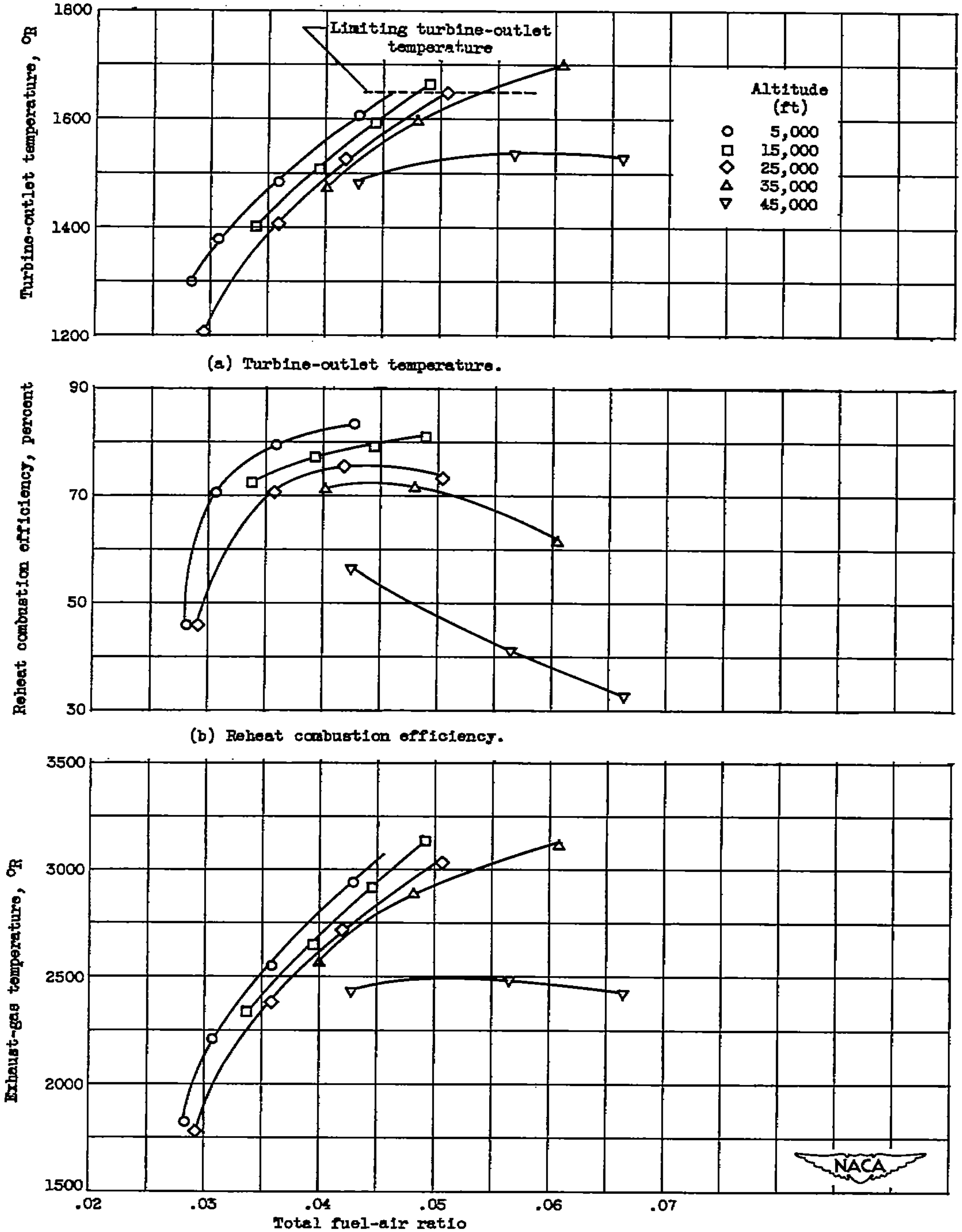
Figure 18. - Effect of exhaust-nozzle area and engine speed on percent rated net thrust. Flight Mach number, 1.05; altitude, 25,000 feet.



(a) Engine A; flight Mach number, 0.26.

(b) Engine B; flight Mach number, 0.52.

Figure 19.- Variation of exhaust-gas temperature with engine speed for two turbojet engines with constant-area exhaust nozzles.



(a) Turbine-outlet temperature.

(b) Reheat combustion efficiency.

(c) Exhaust-gas temperature.

Figure 20. - Variation of turbine-outlet temperature, combustion efficiency, and exhaust-gas temperature with total fuel air ratio for turbojet engine operating with afterburner and two-position exhaust nozzle in open position. Flight Mach number, 0.26. Rated engine speed.

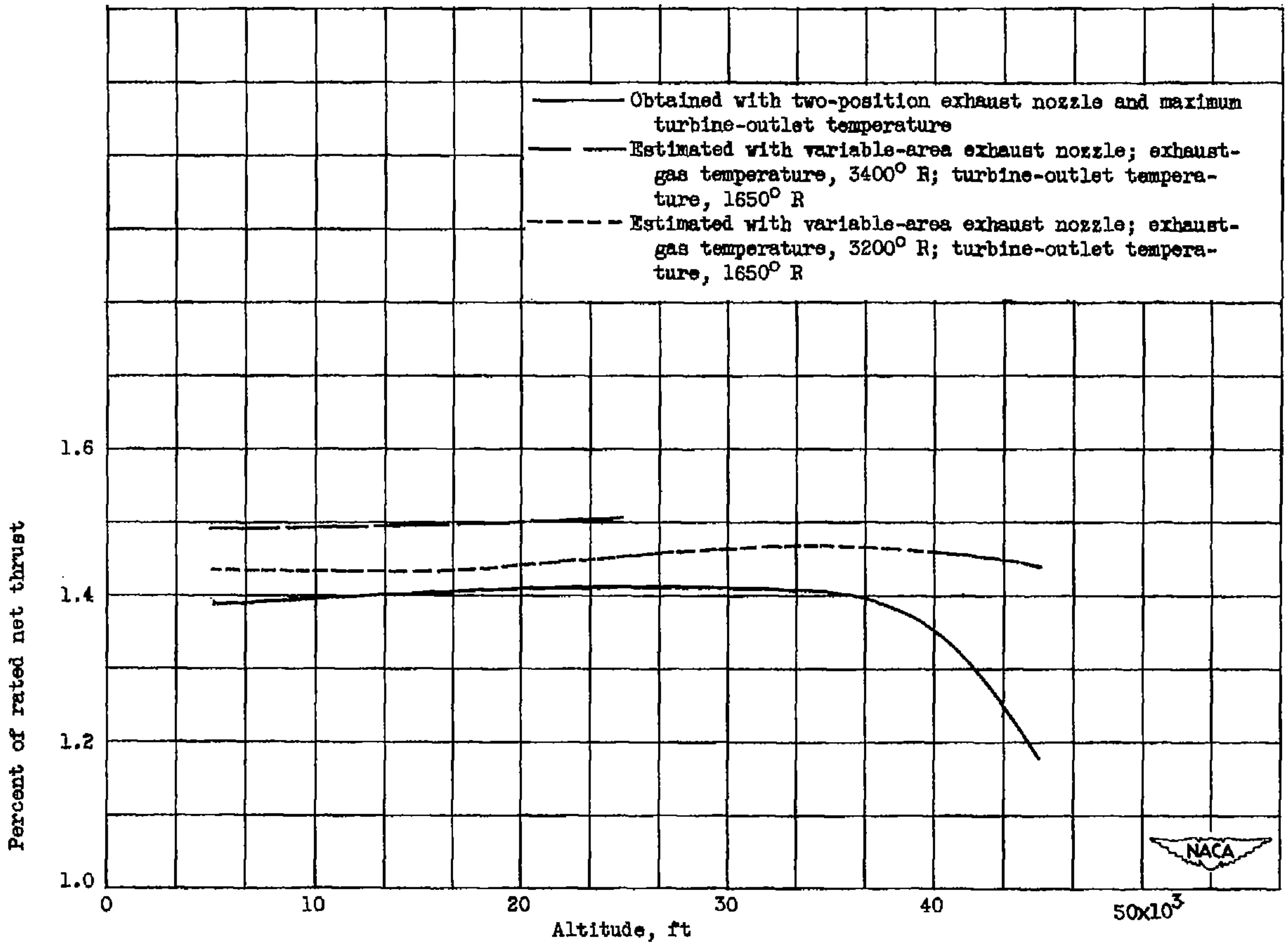


Figure 21. - Variation of net thrust with altitude for turbojet engine with afterburner for two-position and variable-area exhaust nozzlws. Flight Mach number, 0.26; rated engine speed.

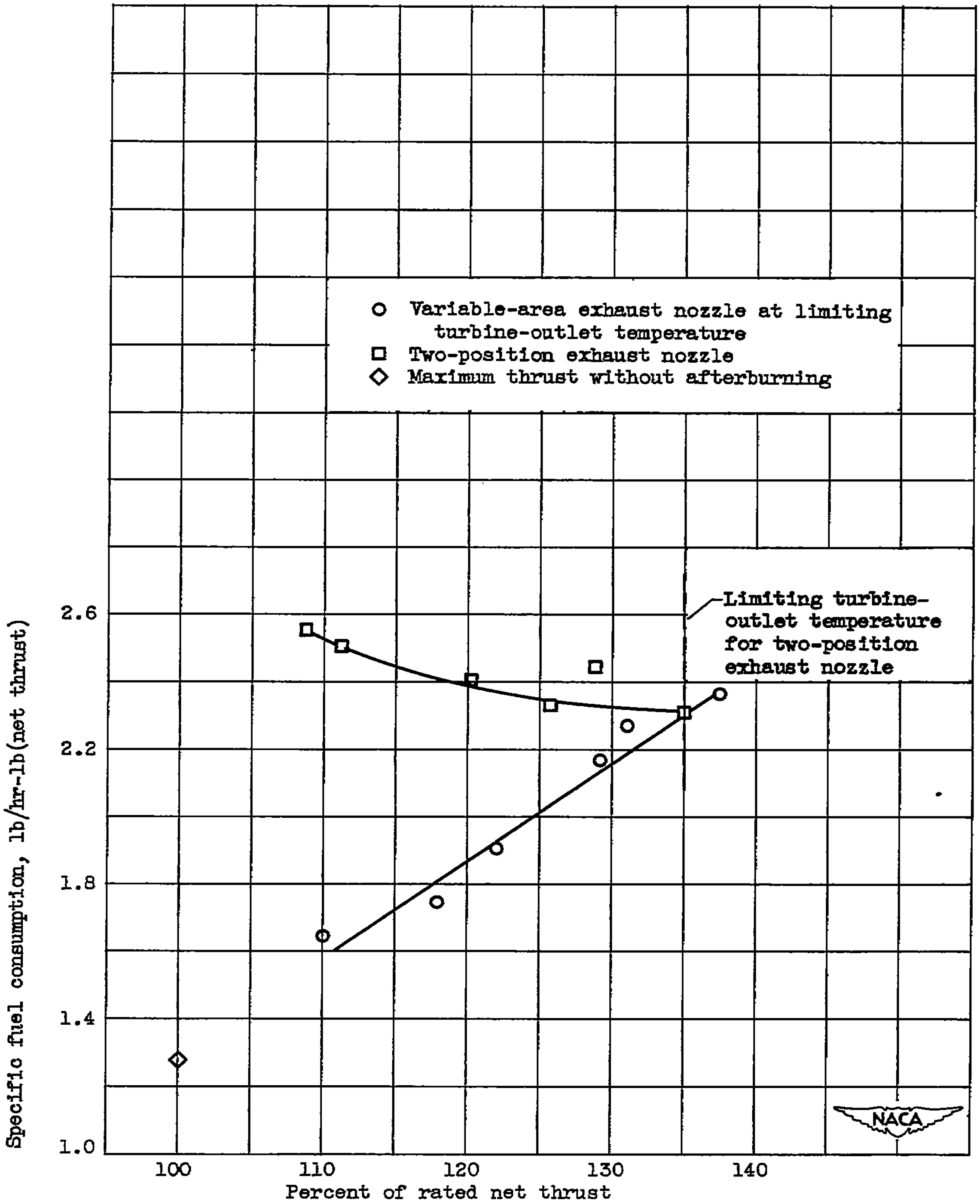


Figure 22. - Variation of specific fuel consumption with net thrust for turbojet engine operating with afterburning and two types of exhaust nozzle. Altitude, 35,000 feet; flight Mach number, 0.26; rated engine speed.